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Microzooplankton Distributions in the Irish Sea

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Microzooplankton distributions in the Irish Sea

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Nova University

1993

Abstract

The purpose of this study was to determine the distributions and abundances of microzooplankton across a front in the Irish Sea, and to test the hypothesis that the structure which develops within the microzooplankton community is the result of the interactions within the communities.

Eight sites were sampled on May 1-2, 1989 along a transect from Liverpool Bay, England to Dundalk Bay, Ireland. The transect crossed both the Liverpool Bay and western Irish Sea fronts; sites were positioned with respect to water type (e.g., coastal, thermally mixed, thermally stratified). Five sites were sampled by double Longhurst-Hardy Plankton Recorder (LHPR) to determine micro- and macrozooplankton distributions and to identify relationships between these distributions and hydrodynamic and biotic forcing. Microzooplankton samples were microscopically enumerated, and the abundance data processed by Correspondence Analysis to determine interrelationships among the taxa.

Variability in depth-averaged microzooplankton distributions along the transect can be explained largely by the hydrodynamic processes associated with the thermal and density structure of the region. The microzooplankton in the coastal and central channel waters were distinct; the Liverpool Bay and western Irish Sea front apparently act as boundaries between microzooplankton assemblages. The

vertical distributions of the microzooplankton at each site appear to be affected by biological interactions between taxa (e.g., predation).

Correspondence Analysis also identified a sub-surface microzooplankton assemblage off the north coast of Anglesey not associated with strong temperature or density gradients, but which was taxonomically distinct from microzooplankton assemblages at the other locations. A similarity between the microzooplankton assemblages in the surface stratified waters of the western Irish Sea front and the Irish coast (48 km west) was also detected. This suggests the possibility that microzooplankton along the Irish coast have been advected offshore in the coastal waters.

Acknowledgements

I would like to thank my major professor, Dr. Gary Kleppel, for his guidance, encouragement and patience throughout this thesis. I thank Dr. Charles Messing for serving on my committee and for his helpful comments. A thank you to Dr. D.V. Holliday (Tracor Applied Sciences, San Diego) for serving as my outside committee member and for providing data incorporated into this thesis.

I would like to thank Dr. Peter Ortner (NOAA, Atlantic Oceanographic and Meteorological Laboratory, Miami) for providing the program to run Correspondence Analysis, and Mr. Kevin Kohler (Nova University) for his assistance in getting the program running on a personal computer.

A special thank you to Dr. Keith Brander (Ministry of Agriculture Fisheries and Food, Lowestoft, U.K.) who provided the samples and data which made this thesis possible.

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Introduction

Microzooplankton range in size from 20 to 200 um in their longest dimension and consist of protozoans as well as holo- and meroplanktonic larvae of metazoans (Sieburth and Smetacek 1978). Microzooplankton can play important roles in marine food webs and geochemical fluxes in the sea (Heinbokel and Beers 1979; Capriulo and Carpenter 1980; Sherr et al. 1986; Berggreen et al. 1988; Graziano 1989; Stoecker and Capuzzo 1990; Gifford 1991; Bockstahler and Coats 1993). Hydrodynamic forcing, may affect the composition and distribution of the microzooplankton. The distribution of microzooplankton can, in turn, affect macrozooplankton production (Stoecker and Egloff 1987) and the survival of larval fishes (Arthur 1977; Stoecker and Govoni 1984; Stoecker and Capuzzo 1990).

The objective of this thesis was to determine the distribution and abundance of microzooplankton across two fronts in the Irish Sea, and to test the hypothesis that the structure which develops within each community is the result of interactions that occur within the microzooplankton community.

The microzooplankton samples which were analyzed in this study, were collected along a transect from Liverpool Bay, England to Dundalk Bay, Ireland (May 1-2, 1989), during a cruise (April 30 to May 11, 1989) aboard the RRV *Cirolana* (MAFF- Ministry of Agriculture, Fisheries and Food, Lowestoft). The cruise was part of a joint project which in-

cluded scientists from MAFF, the Plymouth Marine Laboratory, the University of Liverpool, Tracor Applied Sciences, the University of Southern California, and Nova University. The objectives of this project, which were similar to those of my thesis, were to (1) examine the vertical and horizontal distributions and availability of food to larval fishes, and (2) to determine plankton size distributions and abundances in relation to the hydrodynamic features of the area (Holliday et al. in press).

Background

Physical and Biological Interactions: an Overview

Hydrodynamic variability directly and indirectly affects distributions of micro- and mesozooplankton. Hydrodynamic variability can directly affect microzooplankton distributions because of their small sizes ergo influencing the distributions of mesoplankton which prey on microzooplankton. Fine-scale [1m-100m (Haury et al. 1978)] hydrodynamic variability that affects phytoplankton distributions may indirectly affect the distributions of meso- and microzooplankton. The composition of developing phytoplankton communities depends upon the degree of vertical mixing in the water column (Pingree et al. 1978; Demers et al. 1986). The species in these communities may or may not be nutritious food sources for certain zooplankton and thereby may affect the structure of the zooplankton community.

Fronts are zones of transition between vertically mixed and stratified waters (Demers et al. 1986). The spatial

scale, concentration and duration of localized phytoplankton blooms along a front may be determined by frontal instabilities (e.g., eddies) and by horizontal flow along the front. The evolution of localized phytoplankton patches may be affected by cross-front transfer of nutrients. The strength of horizontal flow and the length of the frontal region may determine whether a phytoplankton patch is dispersed or advected away from an area with favorable growing conditions before it can develop (Pingree et al. 1978). Tintinnids and other protozoans with generation times of 12 to 24 h (Heinbokel 1978) may respond rapidly to environmental variability such as pulses in phytoplankton growth (Capriulo and Carpenter 1980). Coincident protozoan and algae patches may also respond similarly to hydrodynamic forcing, thus maintaining their association (Stoecker et al. 1984). These coincident protozoan and algal patches would provide a concentrated food source for organisms which feed on both.

During phytoplankton blooms, grazing by microzooplankton can serve to transfer some of the energy contained in the phytoplankton to the remainder of the food web (Revelante and Gilmartin 1983). In the absence of grazing, the phytoplankton might sink, exporting energy from the euphotic zone (Capriulo and Carpenter 1980). Stoecker and Sanders (1985) suggested that microzooplankton may be important to the burst of mesozooplankton production which coincides with the spring diatom bloom.

Protozoans and larval metazoans may also play an important role in energy transfer during non-bloom conditions. In many regions, small phytoplankton (<5 um diameter) are quantitatively the most important primary producers, with net-phytoplankton production playing an important role for only a few months in the spring (Joint and Williams 1985). Many adult copepods cannot feed efficiently on particles smaller than 5 um (Paffenhofer 1971; Capriulo and Carpenter 1980; Berggreen et al. 1988). On the other hand, copepod nauplii and other microzooplankton can feed efficiently on the 1-5 um size class.

The C:N ratios of heterotrophic protistans are lower than the ratios found in phytoplankton and mixotrophic protozoans (Stoecker and Capuzzo 1990). Protozoans may be a source of essential nutrients to the mesozooplankton (e.g., polyunsaturated fatty acids, free amino acids and sterols) that may be absent or present only in low concentrations in phytoplankton and non-living material.

Selective feeding, long recognized in the mesozooplankton (Stoecker and Sanders 1985; Stoecker and Egloff 1987; Kleppel et al. 1988, 1991) also occurs among the protozoans. Verity (1991) provided numerous examples of non-random prey acquisition by ciliates and phagotrophic dinoflagellates. Tintinnids may be even more sensitive than the larger zooplankton to changes in the composition of the phytoplankton community (Stoecker et al. 1981). *Favella ehrenbergii* selects dinoflagellates, feeding only occasionally, if at all, on similarly sized phytoplankton such as diatoms and

chlorophytes (Stoecker et al. 1981). During a *Thalassiosira* spp. bloom in Narragansett Bay, tintinnids were not abundant, while copepod nauplii and copepodites were the major grazers. A laboratory experiment revealed that diatoms were unsuitable as a tintinnid food source (Verity 1986).

Physical Environmental Variability in the Irish Sea: Western Irish Sea Front

Coarse-scale processes [1km-100km (Haury et al. 1978)] produce a seasonal temperature front in the western Irish Sea, southwest of the Isle of Man (Beardall et al. 1982). Stagnation of the tidal flow occurs in the area around 54°5′N, 5°40′W (Simpson 1971). The accompanying low level of vertical mixing, increased solar heating (Simpson 1971), and reduced fresh-water run-off from the Irish coast (White et al. 1988) leads to strong stratification near the point of stagnation, and to the formation of a seasonal thermocline which generates the front (Simpson 1971).

Stratification begins in mid-March to early April and is well established by May/June (Fogg et al. 1985a; Hapette et al. 1991) when a horizontal gradient of up to 1°C km^{-1} is often observed at the boundary between the stratified surface water (to the west) and the adjacent vertically mixed water, to the east (Simpson and Hunter 1974; Beardall et al. 1982). The predominant cause of the physical discontinuity is temperature. The stratified surface water to the west is lighter and warmer than the isothermal water to the east,

and is isolated from the "mixed" water by the abrupt surfacing of the thermocline (Beardall et al. 1982).

By early July, changes occur in the chemical characteristics of the surface stratified and mixed waters. Nitrate concentrations increase from west to east across the front, with a pattern similar to that of the isopycnals. The lowest nitrate concentration is in the extreme western surface stratified water. The distribution of silicate tends to be patchy and decreases from west to east across the front (Beardall et al. 1982).

The stability of the stratified water decreases in late July with the warming of the "mixed" water to the east. By September, the thermocline drops from 30 m to 80 m due to cool weather and the weakening of the temperature gradient. The front dissipates by October (Fogg et al. 1985).

Phytoplankton Communities

In the western Irish Sea, distinct phytoplankton communities occur on each side of the front (Beardall et al. 1982). The phytoplankton along the front is a mixture of communities from both sides. Numerically, microflagellates dominate all water types (Beardall et al. 1982), but are most abundant in the surface stratified water where they compose 90% to 98% of the total phytoplankton population (Beardall et al. 1982; Fogg et al. 1985; Turley 1985). Microflagellates comprise 65% and 92% of the population of the mixed water and the front respectively (Beardall et al. 1982).

Diatoms contribute 9% and 27% of the cells in the phytoplankton population in the surface stratified water and the mixed water, respectively (Beardall et al. 1982). Diatoms dominate the phytoplankton biomass in both water masses (Beardall et al. 1982; Fogg et al. 1985). The frontal population is composed of a mixture of species from both water masses, with three out of four transects showing higher species diversities along the front than on either side of it (Beardall et al. 1982).

Zooplankton Communities

Scrope-Howe and Jones (1985) sampled zooplankton distributions across the front in the western Irish Sea in July 1980 and May 1981. They observed that abundances of all copepod life history stages varied spatially. Adult copepods were equally abundant at the front and in the stratified water in May 1981. Nauplii and copepodite abundances were greatest at the front. Hapette et al. (1991) sampled zooplankton distributions across the Irish Sea in April and May 1988 in a study of variations in vitamin C content in sprat larvae. Copepod nauplii were most abundant in the central stratified water and were least abundant in the mixed waters off the Welsh coast.

The distributions of the three most abundant copepod species also varied spatially in May 1981 (Scrope-Howe and Jones 1985). *Pseudocalanus elongatus* nauplii and copepodites, *Oithona similis* and all life history stages of *Acartia clausi* were most abundant at the front. *O. similis* and

all life history stages of *P. elongatus* decreased while *A. clausi* increased in numbers eastward across the front. Scrope-Howe and Jones (1985) did not report the distributions of individual life history stages of *O. similis*.

During the 1980-81 study of the western Irish Sea, estimates of protozoan microzooplankton abundances were not made because samples were filtered onto mesh with an aperture of 142 um (Scrope-Howe and Jones 1986). However, observations suggested that microzooplankton play an important role in heterotrophic cycling of nutrients in the Irish Sea (Fogg et al. 1985b).

Physical and Environmental Variability in Liverpool Bay: Liverpool Bay Front

Liverpool Bay may be described as a system consisting of relatively low salinity coastal water to the east and higher salinity offshore water to the west. In addition, the coastal water is composed of four chemically distinct regions. Differences in physical properties and nutrient concentrations between the coastal and offshore waters are maintained by river outflow and by an offshore north/south density gradient (Liverpool Bay front) which inhibits mixing (Foster et al. 1982a). The front is present year around, but it is intermittent. Stratification associated with the front is only established during periods of calm weather.

During winter, differences in nutrient concentrations between offshore and coastal waters are due to nutrient input from the Mersey, Ribble and Dee rivers (Foster et al.

1982a,b). The offshore water contains relatively high silicate and low total nitrogen concentrations, while the coastal water contains high total nitrogen and low silicate concentrations.

At the beginning of the spring bloom, both nitrate and silicate are available throughout the bay. As the bloom progresses, silicate concentrations decrease more rapidly than nitrate concentrations, and by the end of the bloom, coastal waters can exhibit silicate deficiencies (Foster et al. 1982b).

Phytoplankton Communities

During the spring bloom, phytoplankton abundances decrease moving offshore. Areas of localized high phytoplankton densities composed of varying dominant species can occur in the coastal waters. In May 1977, Foster et al. (1982b) found *Asterionella septentrionalis* (=*A. japonica* Cleve and Möller) and *Navicula* spp. dominated the phytoplankton in the waters off the coast of Lancashire, while *Navicula pelagica* characterized the waters off the coast of Northern Wales. No particular species dominated the offshore water west of the front.

Zooplankton Communities

Between May and July, copepod numbers in Liverpool Bay are highest along the front. The scenario proposed by Floodgate et al. (1981) states that copepods advected into the frontal region experience high concentrations of food

due to the accumulation of detritus and enhanced phytoplankton growth stimulated by bacterial remineralization. This enhanced food environment, in turn, can support increased zooplankton activity, which may be one reason that copepods along the front appear to breed approximately thirty days earlier than copepods elsewhere in Liverpool Bay.

Materials and Methods

Eight study sites were sampled by the RRV *Cirolana* (MAFF) on May 1 and 2, 1989 along a transect from Liverpool Bay to Dundalk Bay. The sites were located in areas where it was believed that the different water types (e.g., coastal, isothermally mixed, thermally stratified; see Background) would be encountered. Each site was sampled with at least two instruments; a station number was assigned to each instrument cast. The stations at each site and the sampling carried out at these stations are listed in Table 1. The locations of the eight study sites are shown in Figure 1. The lines between sites A and B and sites E and F represent the approximate positions of the Liverpool Bay and western Irish Sea fronts.

The microzooplankton samples analyzed in my study were kindly provided by Dr. K. Brander (Ministry of Agriculture, Fisheries, Food, Lowestoft) who supervised the collection of 54 samples by oblique tows of a double Longhurst-Hardy Plankton recorder (LHPR) at five sites along the Liverpool Bay to Dundalk Bay transect. The number of samples collected at each sites was dependent upon water depth (Table 2).

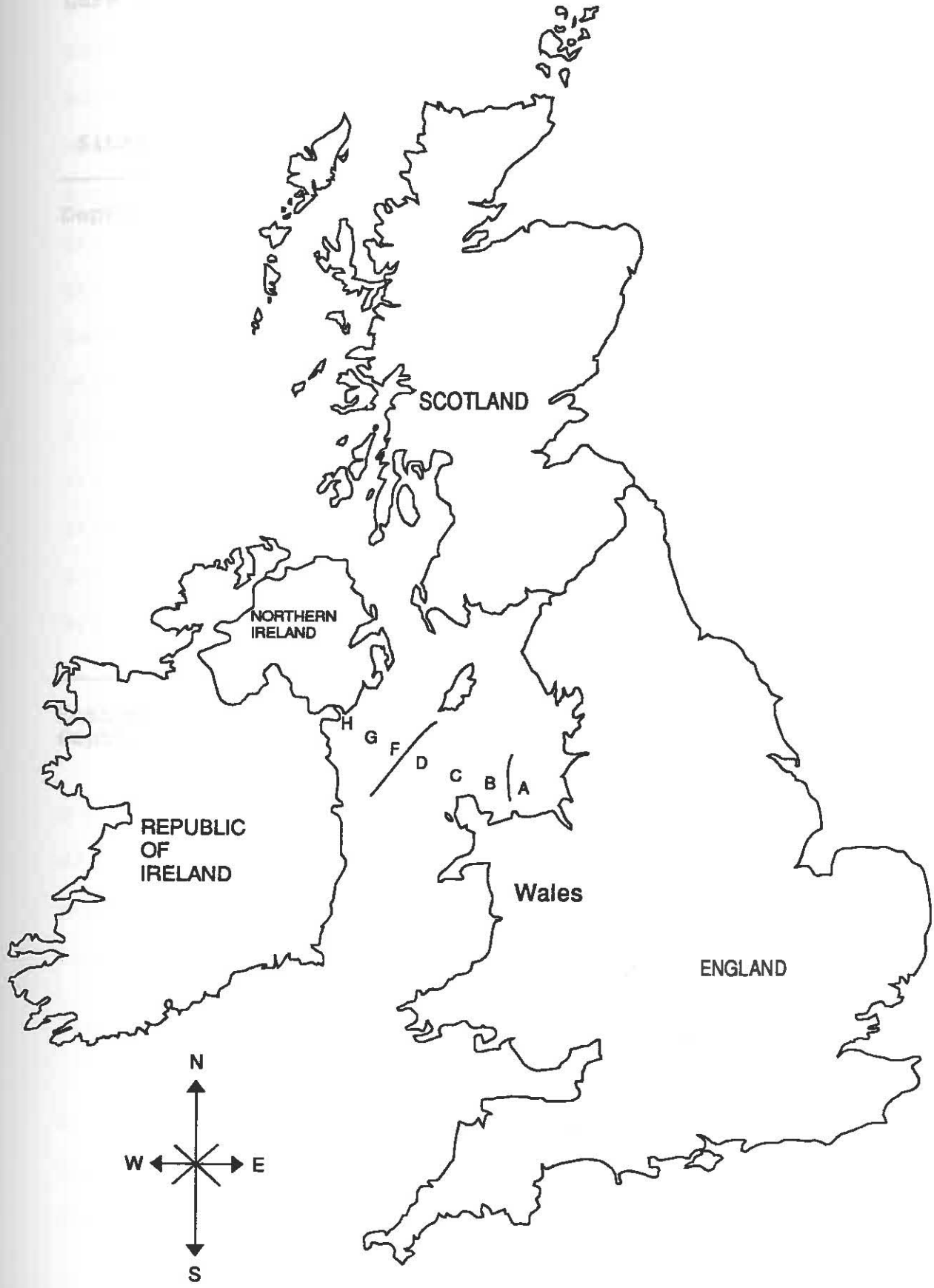
LHPR

The double Longhurst-Hardy Plankton recorder consists of a 280 um mesh macroplankton sampler and a microplankton sampler. This sampler permits study of small scale spatial distributions of zooplankton (Omori and Ikeda 1984). The

Table 1. Study sites along the Liverpool Bay to Dundalk Bay transect, May 1-2, 1989. MAPS=Multi-frequency Acoustic Profiling System (Holliday et al. 1990); LHPR=double Longhurst-Hardy Plankton Recorder (Williams et al. 1983).

SITE	STATION	TIME	POSITION	SAMPLE
A	256	1316-1326	53 27.2 N, 3 44.8 W	CTD
	257	1343	53 27.5 N, 3 44.8 W	MAPS
	258	1434-1447	53 28.1 N, 3 43.2 W	CTD
	259	1525-1539	53 27.3 N, 3 45.4 W	LHPR
B	260	1703-1718	53 30.4 N, 4 02.2 W	CTD
	261	1732	53 30.4 N, 4 00.2 W	MAPS
C	262	1926-1936	53 34.1 N, 4 19.8 W	CTD
	263	1945	53 34.2 N, 4 19.6 W	MAPS
	264	2033-2055	53 33.9 N, 4 19.9 W	LHPR
D	265	750-803	53 38.2 N, 4 39.9 W	CTD
	266	823-832	53 38.0 N, 4 40.0 W	CTD
	267	806-934	53 36.9 N, 4 41.1 W	LHPR
	268	959	53 38.1 N, 4 40.1 W	MAPS
E	269	1208-1220	53 42.4 N, 5 00.6 W	CTD
	270	1236	53 42.5 N, 5 01.4 W	MAPS
F	271	1422-1434	53 46.4 N, 5 20.6 W	CTD
	272	1439	53 46.5 N, 5 20.5 W	MAPS
	273	1541-1604	53 46.1 N, 5 20.5 W	LHPR
G	274	1722-1733	53 51.0 N, 5 40.1 W	CTD
	275	1735	53 53.2 N, 5 40.2 W	MAPS
H	276	1946-1953	53 55.3 N, 6 01.7 W	CTD
	277	2001	53 55.4 N, 6 01.9 W	MAPS
	278	2042-2048	53 55.7 N, 6 02.0 W	LHPR

Figure 1. Study site locations during the Liverpool Bay to Dundalk Bay transect, May 1-2, 1989. Lines represent the approximate positions of the Liverpool Bay (right) and the western Irish Sea (left) fronts.


SCOTLAND
NORTHERN IRELAND
H
G
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REPUBLIC OF IRELAND
Wales
ENGLAND
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S

Table 2. Sampling depth ranges and bottom depths for the 5 LHPR sites along the Liverpool Bay to Dundalk Bay transect.

Sites	H	F	D	C	A
Depth (m)	0-4	6-12	0-2	0-3	0-3
	4-9	12-16	2-6	3-7	3-9
	9-14	16-20	6-12	7-11	9-1
		20-25	12-17	11-15	12-16
		25-28	17-22	15-20	16-18
		28-32	22-27	20-24	18-22
		32-36	27-31	24-28	22-26
		36-40	31-36	28-38	
		40-44	36-40	38-42	
		44-48	40-46	42-46	
		48-50	46-52		
		50-54	52-57		
		54-61	57-60		
		61-66	60-64		
		66-72	64-67		
			67-72		
			72-76		
			76-85		
			85		
Bottom depth (m)	33	81	84-100	52	30

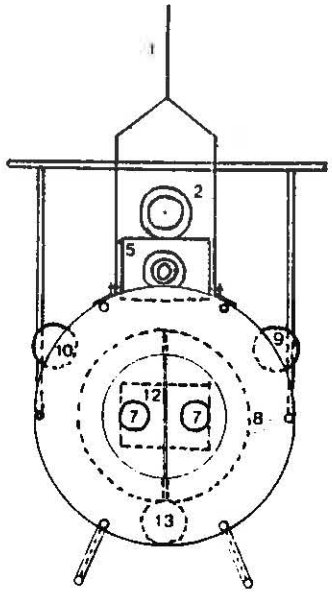
microplankton sampler consists of a nose cone, a plastic inlet tube, a cylindrical net and a Benthos Corporation cod end (Figure 2). A Tsurumi Seiki Kosakusho (TSK) flow meter and a General Oceanic (GO) flow meter are attached in the sleeve joining the two sections of the inlet tube. The microplankton net is 56 cm in length, 11.4 cm in diameter at the mouth and is constructed of 53 um polyester mesh, as are the gauze filters loaded into the cod end (Figure 3). Gauze advances from two feed spools to the flow-through chamber where organisms are collected for a predetermined time interval. The gauze is wound onto the uptake spool (Figure 3), trapping organisms in well defined bands (Williams et al. 1983). A drawback to this system is that samples are compressed and the structures of many organisms are altered, sometimes making identifications difficult. It is usually possible to identify major taxonomic groups, however.

The LHPR was deployed at a steady dive rate, and gauze advanced every 64 seconds, providing samples at an interval of every 2-3 m (Holliday et al. in press). One half splits were made of each sample and preserved with buffered formalin.

Ancillary Data

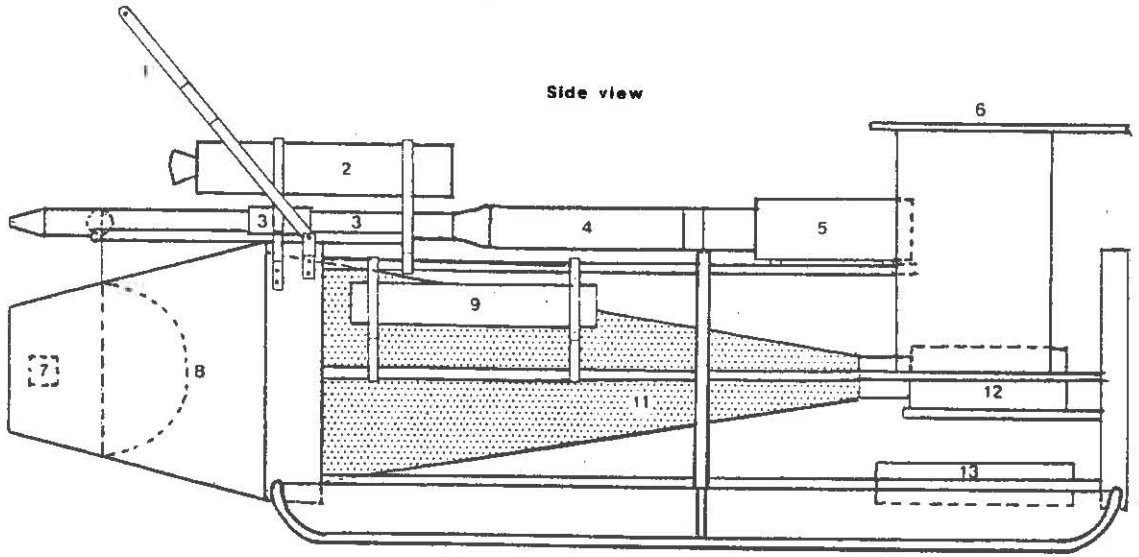
Supporting data from CTD casts were provided by Dr. K. Brander (Ministry of Agriculture, Fisheries and Food, Lowestoft). Plots of chlorophyll *a* values (derived from *in situ* fluorescence measurements) and additional temperature and

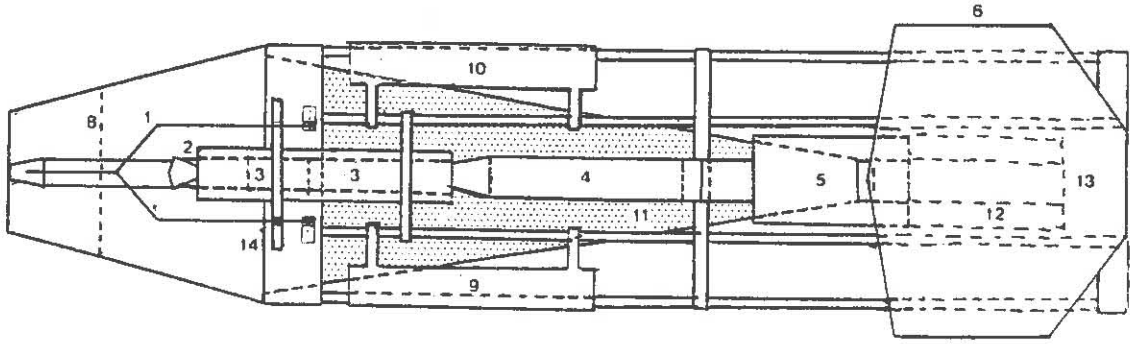
Figure 2. Diagrams of the double Longhurst Hardy Plankton Recorder system. 1. towing bridle; 2. Institute of Oceanographic Sciences net monitor; 3. sites of microplankton sampler flow meters; 4. 53 um net; 5. microplankton LHPR cod end; 6. tail plane; 7. sites of macroplankton sampler flow meters; 8. doors; 9. macroplankton LHPR control unit; 10. microplankton LHPR control unit; 11. 280 um net; 12. macroplankton LHPR cod end; 13. door timer control unit; 14. bridle travel-limiting stop (from Williams et al. 1983).



Front view

Side view

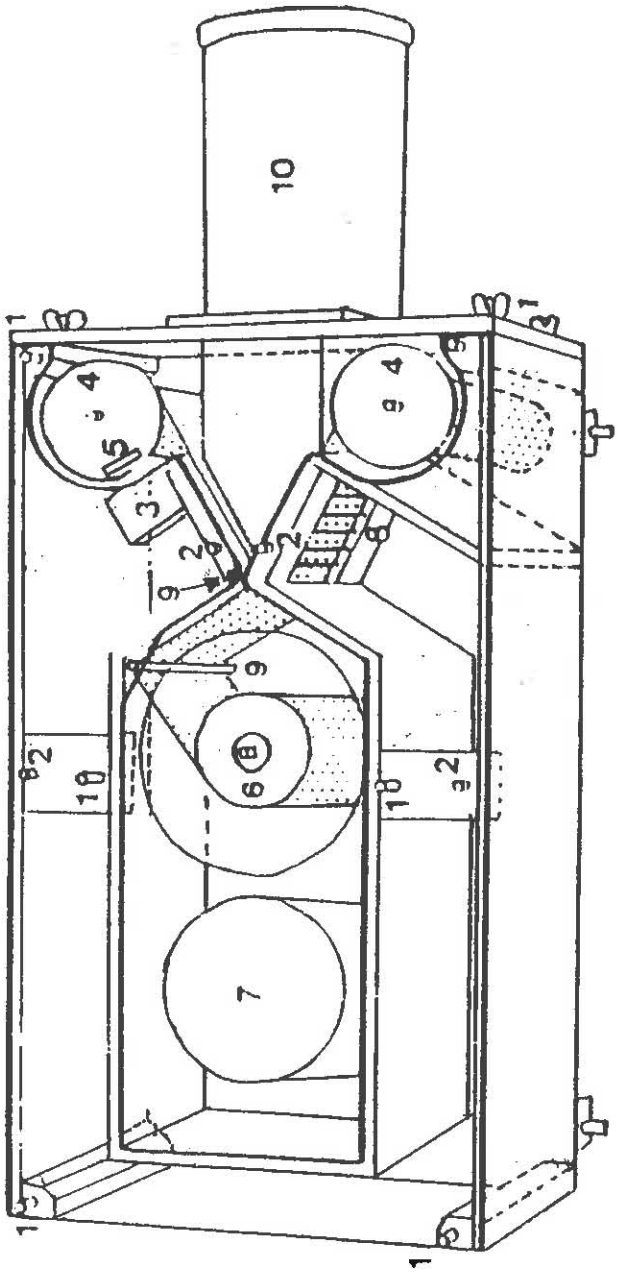




Top view

1 m

Figure 3. Institute for Marine Environmental Research modified LHPR cod-end box (5 in Figure 2) with lid removed. 1. Screws and wing-nuts for securing lid and front section; 2. dowels; 3. Electro-Oceanics reed switch; 4. feed spool; 5. magnet in-feed spool end cap; 6. take-up spool; 7. motor; 8. support bars; 9. rollers; 10. inlet tube. False top is shown by heavy outline. Gauze is shown stippled (From Williams et. al. 1983).


10
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salinity plots were generously provided by Dr. D.V. Holliday (Tracor Applied Sciences). These data were collected by MAPS (Multi-frequency Acoustic Profiling System) casts which were performed by Drs. D.V. Holliday (Tracor Applied Sciences) and R.E. Pieper (University of Southern California).

Sample Processing

Microzooplankton samples were counted in a Sedgwick-Rafter chamber at 100x magnification with an Olympus CK2 inverted light microscope. Each sample was shaken until all particulate material (microplankton and detritus) was evenly distributed. One milliliter from each sample was immediately removed and examined under the microscope. Addition aliquots were examined until at least two-hundred organisms were counted. Identifications were made to genus or species where possible, but taxonomic description in some cases was limited to class or family. Lee et al. (1985), Sieburth (1979), Yamaji (1974) and Whimpenny (1976) served as sources of information for identification of organisms.

Samples were examined to determine the nauplius genera composition and whether genera varied with depth. Identification was limited by the condition of the organism and the detail of the taxonomic key (Yamaji 1974). The lengths of the nauplii were measured to determine whether length, as an indicator of age, varied with depth. The results were inconclusive, because the mean lengths of the nauplii of each species at the various depths were not significantly

different.

Surface LHPR samples were examined to determine the composition of the phytoplankton at sites A,C,D,F and H. However, because samples were filtered onto 53 um gauze, phytoplankton compositions were biased for larger cells.

The center depths of the sample depth ranges were used for plotting the bathymetric distributions of the microzooplankton and composition of copepod nauplii populations.

Statistical Analysis

Statistical analysis was limited to 16 recurrent taxonomic groups. That is, these 16 groups occurred in at least 48% of the samples (Table 3), and were present at 4 of the 5 LHPR stations. *Gymnodinium* sp. was included in the analysis because it was detected in large numbers along the entire transect, and it was not determined whether this dinoflagellate was heterotrophic or autotrophic. *Distephanus* sp., a silicoflagellate, was included because it was present in 48% of the samples. The Foraminifera group consists of all genera except *Globigerina* sp. Ghost eggs are empty egg cases.

Chi-square goodness of fit tests were performed to test the hypothesis that the microzooplankton abundances were normally distributed. The hypothesis was rejected in all cases. The data were then log transformed [x=log(x+1)] and Chi-squared goodness of fit tests were again performed to test the hypothesis that the log transformed abundances of the taxonomic groups were normally distributed. The

Table 3. The sixteen most often encountered taxonomic groups present in at least 48% of samples. Abundances of certain (*)groups may be artificially low, because their dimensions may allow them to pass though the gauze used in the LHPR (53 um).

copepod nauplii	Foraminifera
copepodites	*Globigerina* sp.
* *Tintinnopsis* spp.	Appendicularia
* aloricate ciliates	veliger larvae
Protoperidinium spp.	* 50 um eggs
Ceratium spp.	70-80 um copepod eggs
* *Gymnodinium* sp.	90-100 um copepod eggs
* *Distephanus* sp.	ghost eggs

hypothesis of normality was tested and rejected in 11 of 16 cases. Therefore, distribution free statistics were utilized in this study.

Correspondence Analysis

Correspondence analysis, a non-parametric form of Factor Analysis, was used to identify interactions between the microzooplankton distributions over the entire data set. The program used in this analysis was obtained from Dr. P.B. Ortner (NOAA, Atlantic Oceanographic and Meteorological Laboratory, Miami), and was modified to run on an IBM-compatible personal computer by Mr. K. Kohler (Nova University).

Correspondence Analysis was used because it evaluates the interrelationships among all variables. Regression Analysis typically performs pair-wise evaluation of relationships between variables (Morey-Gaines 1980), and can be further used to explore relationships between sets of variables in interacting groups. Multiple Regression may be used to create a regression equation to determine the mathematical relationship between several independent variables and a dependent variable. However, in order to select the proper variables to produce a meaningful model, it is important to understand the interrelationships among the variables (Zar 1974).

Correspondence Analysis is distribution free and tolerant of missing (zero) data points (Ortner et al. 1989), unlike Principal Components Analysis (another form of Factor

Analysis) which makes the assumption that the data are normally distributed (Harris 1985). Because the data used herein are not normally distributed, this assumption would have been violated.

Data are entered into a 2-dimensional matrix (Ortner et al. 1989). A coordinate system is produced wherein microzooplankton abundances are coordinates of the taxonomic groups (p) and the samples (n). An equation transforms the data set so that samples and species are in "correspondence" and can be placed on the same set of axes (Morey-Gaines 1980).

The goal of this analysis is to summarize the data in less than the original number of axes (i.e., the number of samples). This will cause some loss of the ability to detect variance. To minimize this loss, the greatest possible amount of the original variance is contained in the first few "new" axes or factors. The first factor is rotated about the origin until it is centered along the greatest spread of points, thus explaining the greatest variance (major trend) in the data. The amount of variance extracted by a factor is called an eigenvalue (Lawley and Maxwell 1971). This process is repeated, centering each subsequent factor along the greatest remaining variance. Each factor will be orthogonal, that is independent, of the previous factor. The coordinates, or scores, of each data point will change as the factors are rotated, but the position of that data point in space with respect to the positions of the other data points will not change (Morey-Gaines

1980).

The results of the Correspondence Analysis can be presented as three dimensional scatter plots. The eigenvalues for the taxonomic groups and samples can be plotted on axes representing the first three factors (Ortner et al. 1989).

Correlation Analysis

Spearman Rank Order Correlation Coefficients were calculated to describe the relationship between pairs of major taxonomic groups, chlorophyll *a* concentrations and physical variables for the transect and for sites A, C, D and F. Correlation coefficients were not calculated for site H because of the low number of data pairs at the LHPR station at this site (n=3). Correlation coefficients were not calculated for sites B, E and G because there were no LHPR stations at these sites.

RESULTS

Physical Environmental Variabilities

The waters off the Welsh and Irish coasts (study sites A and H, respectively) were stratified (Figures 4-6), with relatively warm, less saline water overlying cooler, higher salinity water that characterized the waters offshore. Site A was located to the east of the intermittent Liverpool Bay front which runs along 4°W line of longitude from Great Orme Head, Wales. The water column at site H, west of the western Irish Sea front, was more strongly stratified than at site A. Sharp temperature and sigma-t gradients occurred at depths between 10 and 20 m at site H while no sharp gradients existed at site A.

Sites F and G, also west of the western Irish Sea front, were also thermally stratified. However, the temperature of the upper mixed layer was lower at site G (8.6° C) than at site F and H (9.1° C and 8.9° C, respectively). The densest water observed along the transect was present at site F below 20 m (sigma-t=26.6), while the coldest temperature was measured at site G at 85.5 m (7.9° C). Two thermoclines were present at site G, one at 20 m and the other at ca. 48 m. This similar but less defined thermal layering was present at site F.

Distributions of physical environmental variables at sites B, C, D and E (i.e., sites located in the isothermal region) were similar. The water column was isothermal below 8 m at each of these sites. On average, salinity

Figure 4. Temperature (° C) contours for the Liverpool Bay to Dundalk Bay transect. May 1-2, 1989. Data provided by Dr. K. Brander.

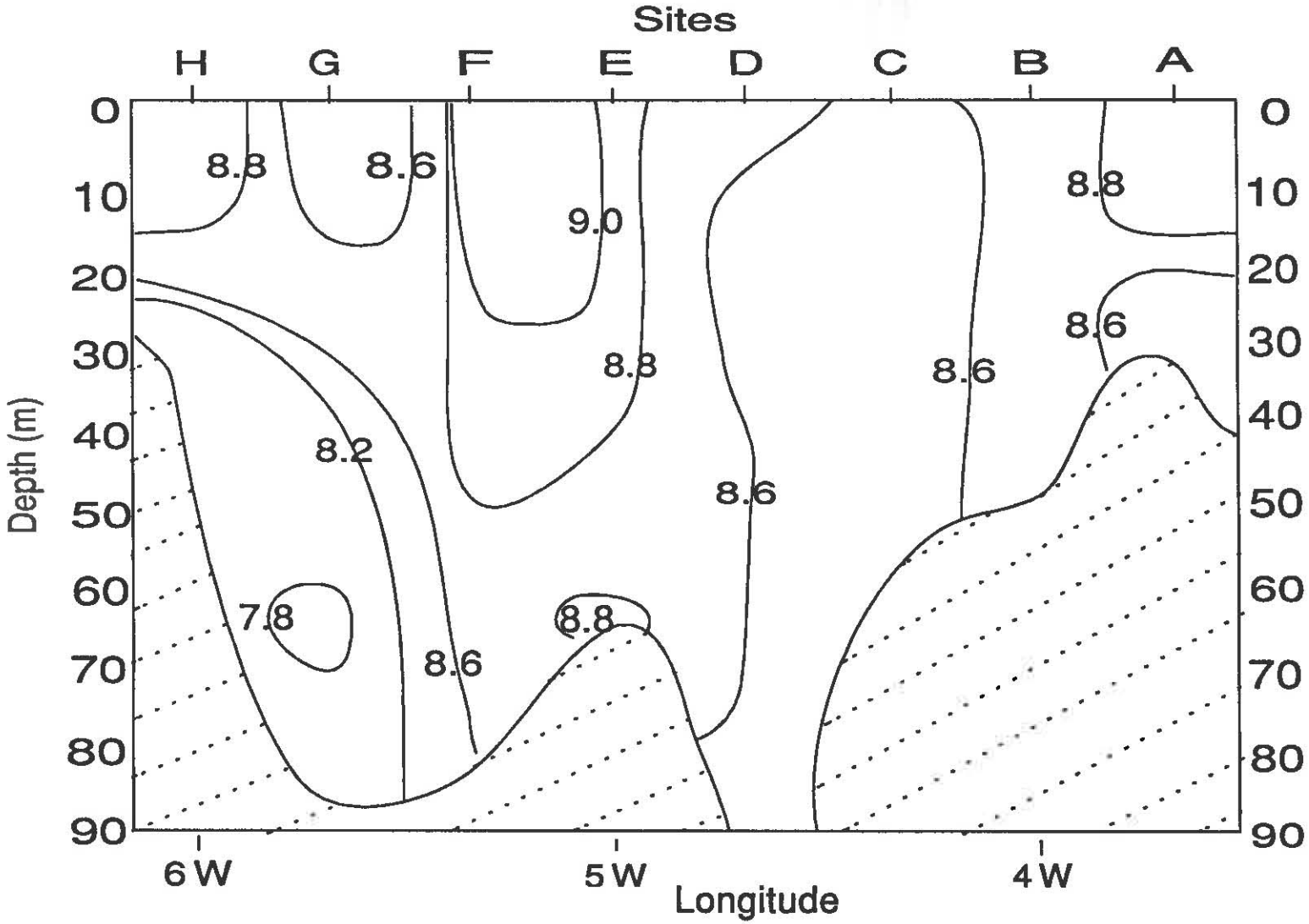

Sites
H
G
F
E
D
C
B
A
0
10
20
30
40
50
60
70
80
90
Depth (m)
8.8
8.6
9.0
8.8
8.6
8.8
8.6
8.2
8.6
7.8
8.8
8.6
6 W
5 W
4 W
Longitude

Figure 5. Salinity (ppt) contours for the Liverpool Bay to Dundalk Bay transect. May 1-2, 1989. Data provided by Dr. K. Brander.

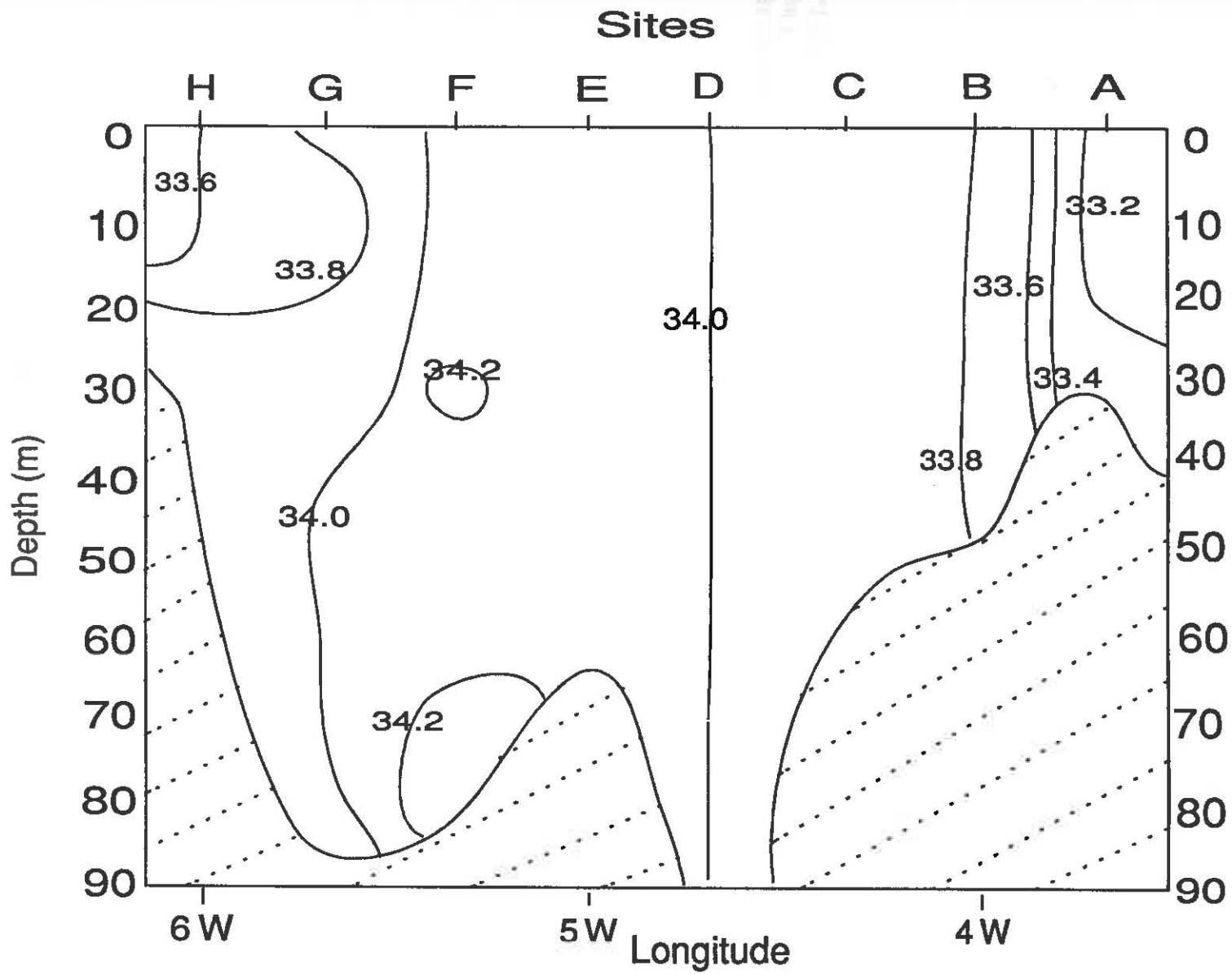
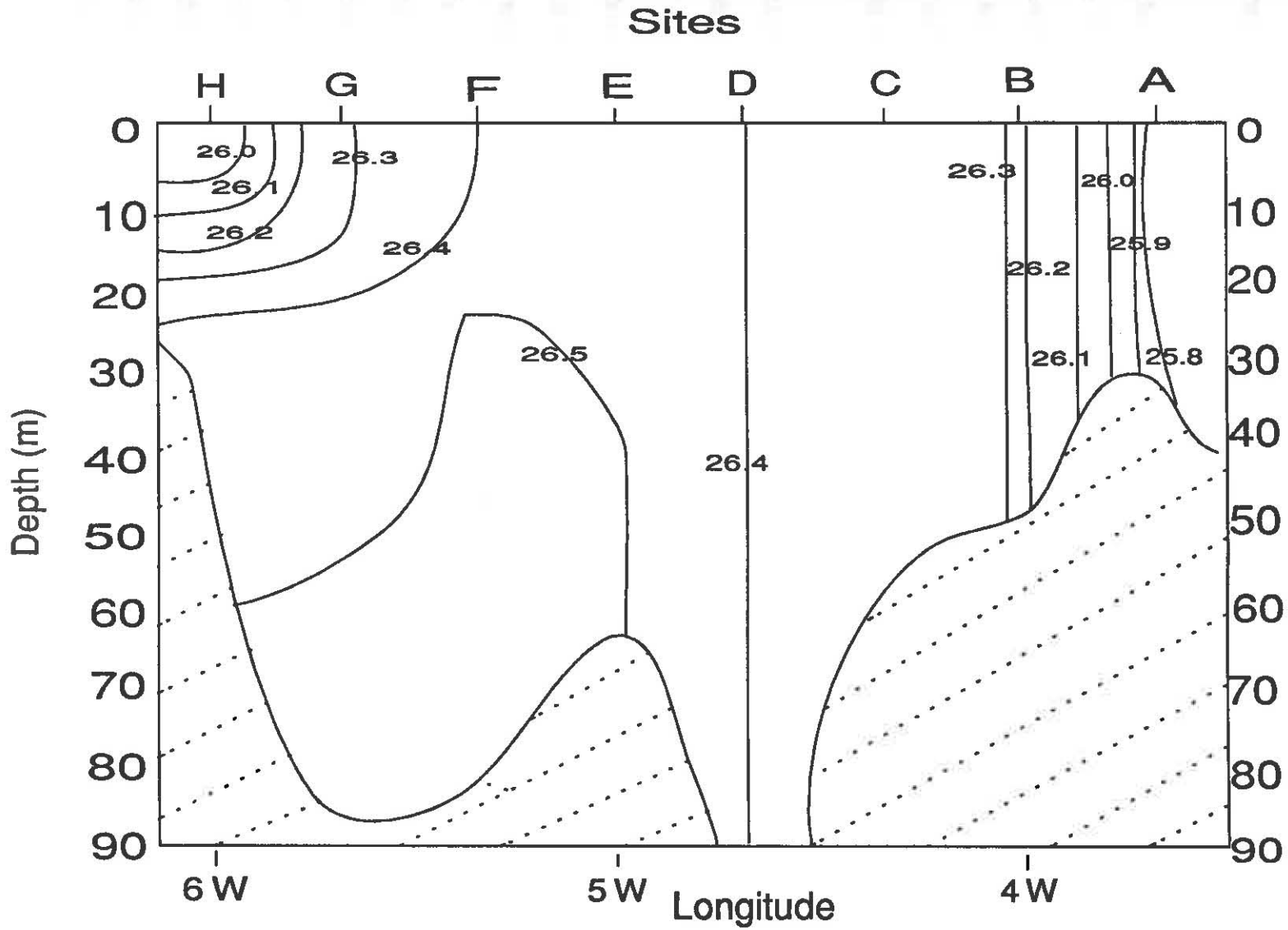

Sites
H
G
F
E
D
C
B
A
0
10
20
30
40
50
60
70
80
90
Depth (m)
33.6
33.8
34.0
34.2
34.0
34.2
33.6
33.2
33.4
33.8
6 W
5 W
4 W
Longitude

Figure 6. Sigma-t contours for the Liverpool Bay to Dundalk Bay transect. May 1-2, 1989. Data provided by Dr. K. Brander.


Sites
H
G
F
E
D
C
B
A
0
10
20
30
40
50
60
70
80
90
Depth (m)
26.0
26.1
26.2
26.3
26.4
26.5
26.4
26.3
26.0
25.9
26.2
26.1
25.8
6 W
5 W
4 W
Longitude

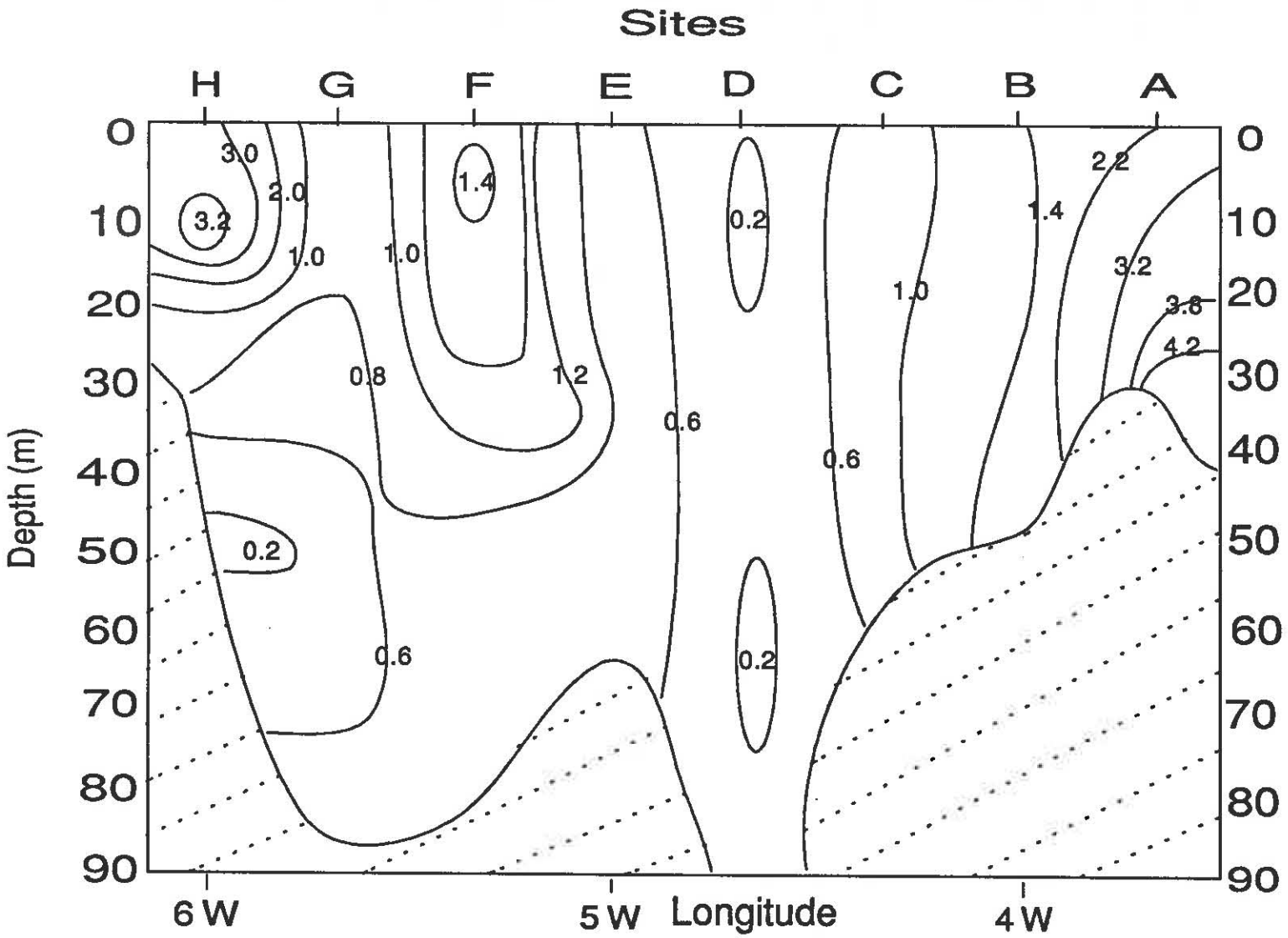
increased ca. 0.1 ppt per site from site C to E, with a corresponding increase in sigma-t.

Chlorophyll Distributions

The highest surface chlorophyll concentrations along the transect occurred off the Irish and Welsh coasts [3.0 mg m^{-3} and 2.2 mg m^{-3} (Figure 7)]. The surface chlorophyll concentration in the stratified region immediately west of the front (site F) was approximately double that at site G further west and site E east of the front (1.4, 0.8, and 0.7 mg m^{-3}, respectively).

Increases in chlorophyll concentration appear to coincide with increases in temperature (see below). Chlorophyll concentration decreased below the thermocline at sites F and H (a decrease of 0.3 and 2.4 mg m^{-3}, respectively). The central mixed region (sites C, D and E) had high levels of nutrients, and low chlorophyll concentrations and water temperatures. Chlorophyll concentrations were low at site G, despite conditions favorable for phytoplankton growth (i.e., nutrients and light were not limiting). However, the temperature of the upper mixed layer at site G was equal to the lowest surface temperature measured at a mixed water site (8.6° C at site C). Site A off the coast of Wales, where the highest chlorophyll concentration was in the coolest and deepest sample from this site (4.3 mg m^{-3}; 8.5° C; 30 m) was an exception.

Figure 7. Chlorophyll *a* (mg/m^3) contours for the Liverpool Bay to Dundalk Bay transect May 1-2, 1989. Data provided by Dr. D.V. Holliday.


Sites
H
G
F
E
D
C
B
A
0
10
20
30
40
50
60
70
80
90
Depth (m)
3.0
2.0
3.2
1.0
1.0
1.4
0.8
1.2
0.6
0.2
0.6
0.2
0.2
1.0
0.6
1.4
2.2
3.2
3.8
4.2
6 W
5 W
4 W
Longitude

Microzooplankton Distributions: Site by site descriptions

Site A: Welsh coast (east of the Liverpool Bay front)

Seven depth intervals were sampled by LHPR between the surface and 26 m (Table 2). Seven of 14 groups detected at this station had bi-modal distributions (Figure 8 a-g). In general, the highest abundances of microzooplankton were detected in samples collected above 12 m and below 16 m. *Globigerina* sp. and 50 um eggs were absent.

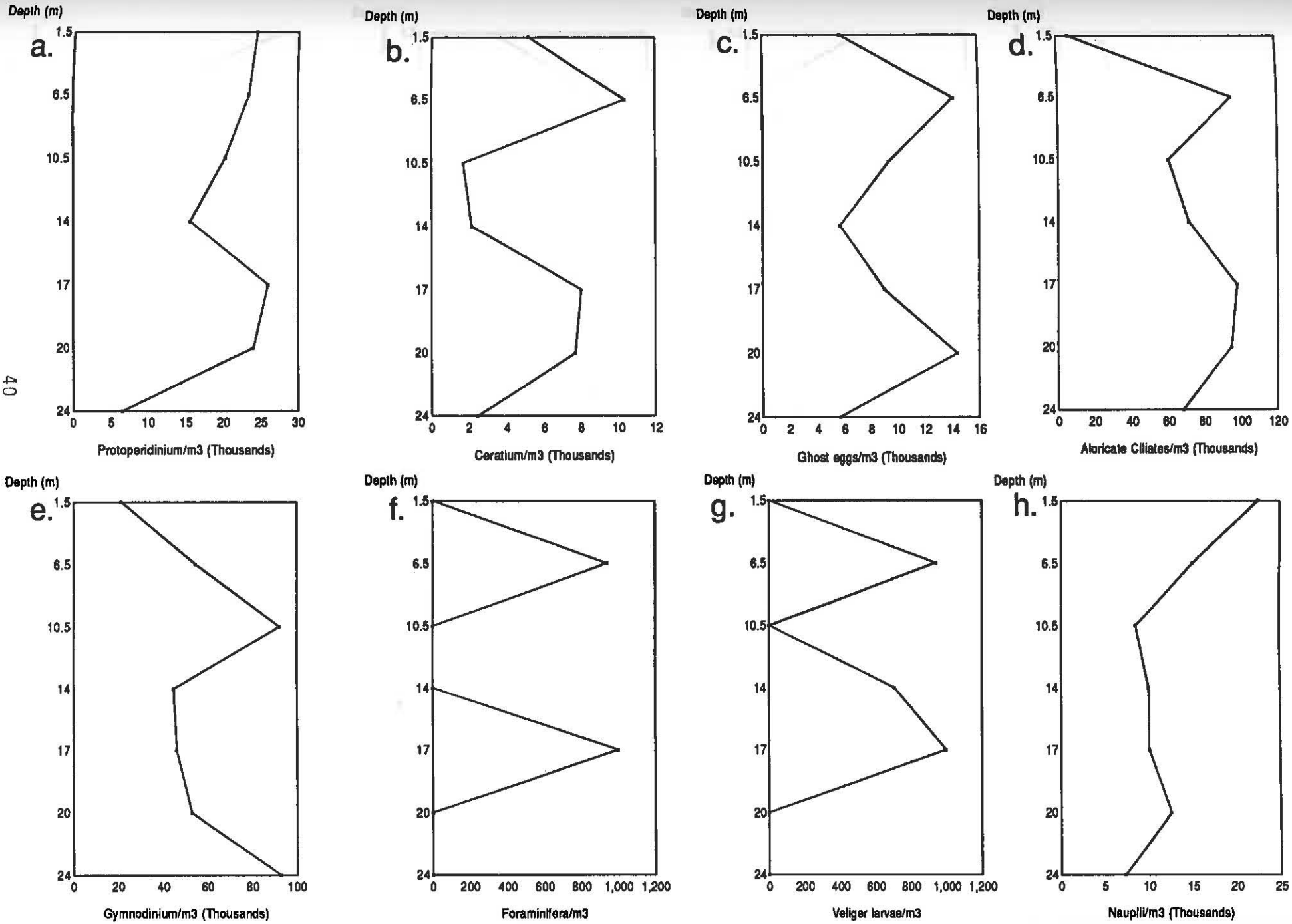
Copepod nauplii, 90-100 um copepod eggs and 70-80 um copepod eggs (Figures 8 h-j) were most abundant in the upper 9 m. *Distephanus* spp., Appendicularia and *Tintinnopsis* sp. (Figures 8 k-m) were most abundant below 12 m. Unlike the other groups, copepodites (juvenile copepods) were most abundant in the 12-16 m sample (Figure 8 n).

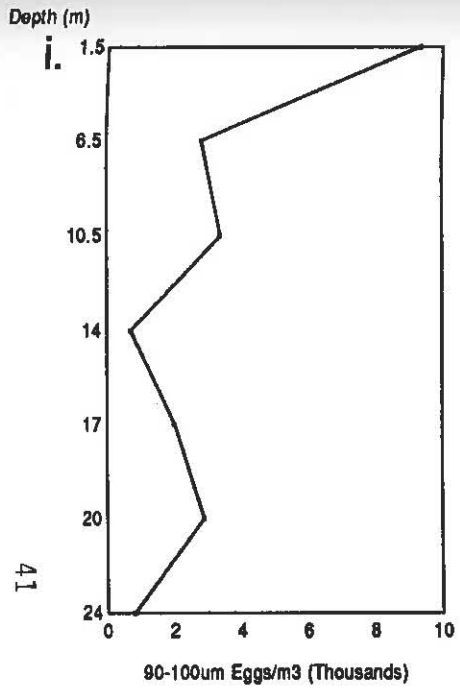
Acartia sp. and *Eurytemora* sp. nauplii dominated the abundance peaks at the surface and 18-22 m (Figure 9). *Acartia* sp. was most abundant at the surface and *Eurytemora* sp. at 18-22 m. *Calanus* sp. nauplii occurred in small numbers in both samples.

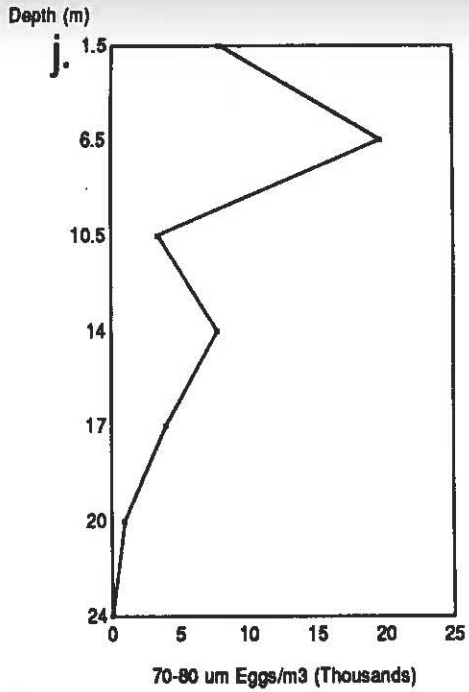
Fifteen diatom species were detected at this site (Table 4), including *Eucampia*, *Lauderia*, *Nitzschia seriata* and *Thalassiosira*. *Asterionella japonica* was overwhelmingly dominant.

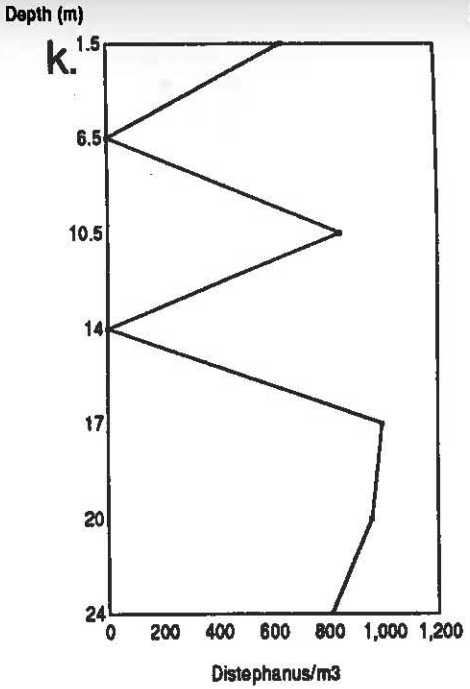
Spearman Rank Order Correlation Coefficients used to describe the relationship between the abundances of the microzooplankton groups, physical environmental variables and chlorophyll concentrations at this site are presented in

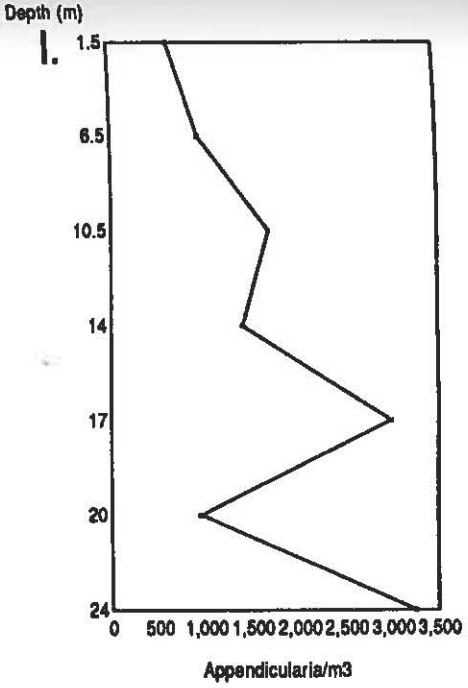
Figure 8. Vertical distributions of the taxonomic groups at site A. Depths indicate the center of each sampling range.

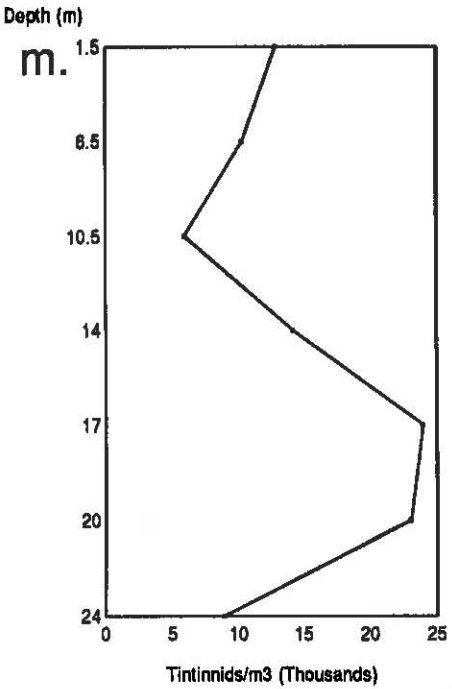

a.
Depth (m)
1.5
6.5
10.5
14
17
20
24
0 5 10 15 20 25 30
Protoperidinium/m3 (Thousands)
b.
Depth (m)
0 2 4 6 8 10 12
Ceratium/m3 (Thousands)
c.
Depth (m)
0 2 4 6 8 10 12 14 16
Ghost eggs/m3 (Thousands)
d.
Depth (m)
0 20 40 60 80 100 120
Aloricate Ciliates/m3 (Thousands)
e.
Depth (m)
0 20 40 60 80 100
Gymnodinium/m3 (Thousands)
f.
Depth (m)
0 200 400 600 800 1,000 1,200
Foraminifera/m3
g.
Depth (m)
0 200 400 600 800 1,000 1,200
Veliger larvae/m3
h.
Depth (m)
0 5 10 15 20 25
Naupli/m3 (Thousands)


Depth (m)
i.
1.5
6.5
10.5
14
17
20
24
0
2
4
6
8
10
90-100um Eggs/m3 (Thousands)


Depth (m)
j.
1.5
6.5
10.5
14
17
20
24
0
5
10
15
20
25
70-80 um Eggs/m3 (Thousands)


Depth (m)
k.
1.5
6.5
10.5
14
17
20
24
0
200
400
600
800
1,000
1,200
Distephanus/m3


Depth (m)
l.
1.5
6.5
10.5
14
17
20
24
0
500
1,000
1,500
2,000
2,500
3,000
3,500
Appendicularia/m3


Depth (m)
m.
1.5
6.5
10.5
14
17
20
24
0
5
10
15
20
25
Tintinnids/m3 (Thousands)

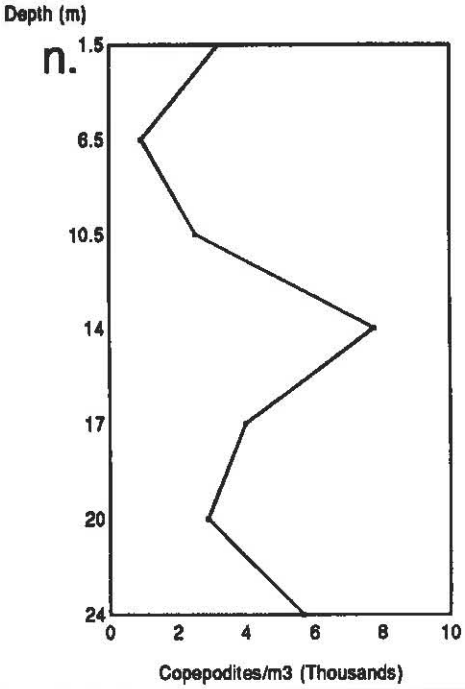

Depth (m)
n.
1.5
6.5
10.5
14
17
20
24
0
2
4
6
8
10
Copepodites/m3 (Thousands)

Figure 9. Compositions of the copepod nauplius populations in two samples at site A. Depths indicate the center of each sampling range.

Nauplius Population Composition
Site A

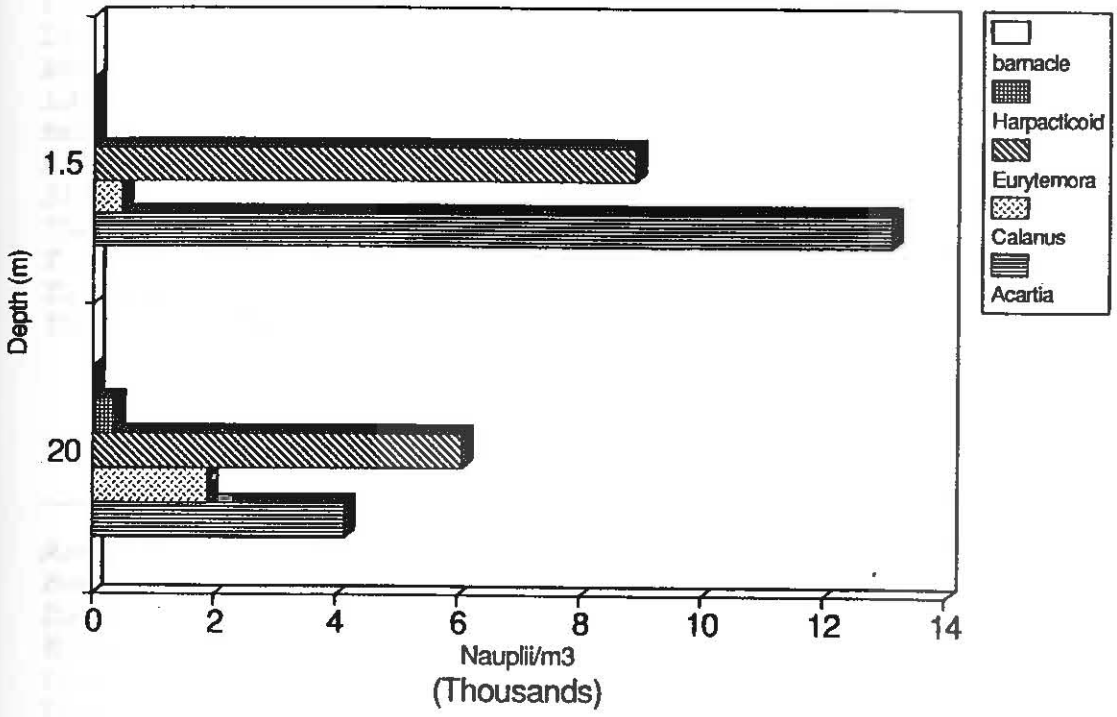


Table 4. Phytoplankton species list for the 5 LHPR sites of the first southern transect of the Irish Sea. Only the surface samples were examined for species composition.

Site A

Asterionella japonica
Bacteriosira fragillis
Biddulphia sinensis
B. granulata
Coscinodiscus lineatus
Ditylum brightwellii
Eucampia zoodiacus
Lauderia borialis
Melosira jüergensi
Nitzschia seriata
Streptotheca thamensis
Thalassiosira bioculata
T. gravida
T. hyalina
Thalassionema nitzschiodes

Site C

Asterionella japonica
Bacillaria paradoxa
Bacteriosira fragillis
Biddulphis sinensis
Chaetoceros teres
Coscinodiscus lineatus
Ditylum brightwellii
Fragilaria oceanica
Lauderia borealis
Nitzschia closterium
N. seriata
Paralia sulcata?
Pleurosigma sp.
P. elongatum
Streptotheca thamensis
Thalassiosira sp.
Thalassiosira bioculata

Site D

Asterionella japonica
Bacillaria paradoxa
Bacteriosira fragillis
Biddulphia sinensis
Coscinodiscus lineatus
Ditylum brightwellii
Fragilaria oceanica
Nitzschia seriata
N. sigma
Pleurosigma elongatum
Skeletonema costatum
Streptotheca thamensis
Thalassiosira sp.

Site F

Actinoptychus undulatus
Bacillaria paradoxa
Bacteriosira fragillis
Biddulphia sinensis
Chaetoceros sp.
C. socialis
Coscinodiscus sub-bulliens
Dityllum brightwellii
Hyalodiscus stelliger
Lauderia borealis
Nitzschia closterium
N. seriata
N. sigma
Stephanopyxis turris
Streptotheca thamensis
Thalassiosira gravida
T. nitzschoides
T. nordenskjoldii
T. rotula

Site H

Bacillaria paradoxa
Biddulphia sinensis
Chaetoceros sp.
C .socialis
Ditylum brightwellii
Lauderia borealis
Nitzschia seriata
Rhizosolina styliformis

Table 5. Of the microzooplankton taxonomic groups at this station, only the abundance of 70-80 um copepod eggs was significantly correlated with variables in the physical environment. The abundance of 70-80 um eggs was positively correlated with temperature, and negatively correlated with salinity and sigma-t. However, the number of data pairs at this site was low (n=7); thus the correlation coefficients must be interpreted cautiously.

Site C: North Anglesey coast

LHPR samples were collected at ten depths between the surface and 46 m (Table 2). The water column at this site was isothermal. However, all taxonomic groups, with the exception of *Gymnodinium* sp., copepod nauplii, *Distephanus* sp. and Appendicularia (Figures 10 e,h,k,l), were more abundant below than above 38 m. Copepod nauplii were most abundant at 20-24 m, while *Distephanus* sp. was abundant at the surface and at 38-42 m. Appendicularia were only detected in the sample collected at 11-15 m.

Protoperidinium spp., aloricate ciliates, 90-100 um copepod eggs and 50 um eggs were most abundant at 42-46 m (Figures 10 a,d,i,o). Each remaining taxon reached peak abundance in the 38-42 m sample (Figures 10b,c,f,g,j,m,n,p).

Compositions of copepod nauplius populations detected in the surface, 20-24 m and 42-46 m sample are shown in Figure 11. *Calanus* and *Acartia* occurred in large numbers at all three depths and were most abundant at 22-24 m. Barnacle and *Eurytemora* nauplii occurred in low numbers at

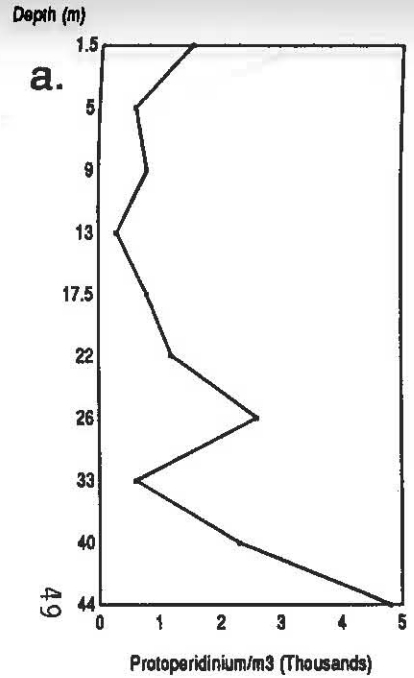
Table 5. Spearman rank order correlation coefficients for site A (n=7; p<0.05=0.786). Abbreviations used in this table: cope- copepodites; tint-*Tintinnopsis* spp.; a cili- aloricate ciliates; Proto-*Protoperidinium* spp.; Gymno-*Gymnodinium* sp.; Dist-*Distephanus* sp.; Globi-*Globigerina* sp.; chl a-chlorophyll *a*.

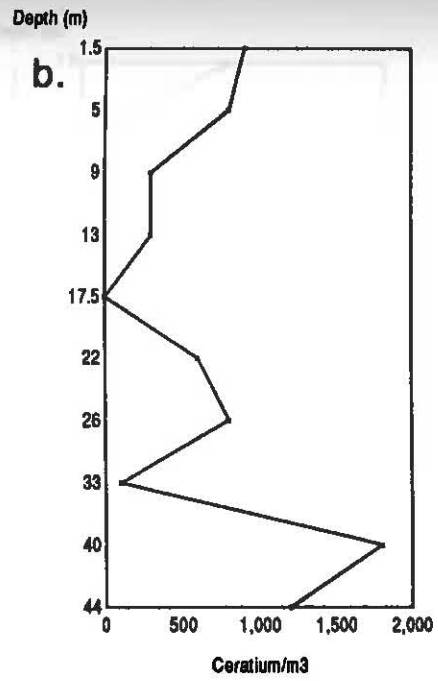
	nauplii	cope	tint	a cili	Proto	Ceratium	Gymno	Dist	Forams
nauplii	1.000								
cope	-0.429	1.000							
tint	0.393	0.321	1.000						
a cili	0.071	0.000	0.714	1.000					
Proto	0.714	-0.286	0.643	0.357	1.000				
Ceratium	0.643	-0.357	0.500	0.643	0.607	1.000			
Gymno	-0.643	-0.286	-0.643	0.000	-0.571	-0.143	1.000		
Dist	-0.198	-0.360	0.360	0.414	0.468	0.090	0.162	1.000	
Forams	0.267	-0.223	0.401	0.668	0.535	0.757	-0.045	0.202	1.000

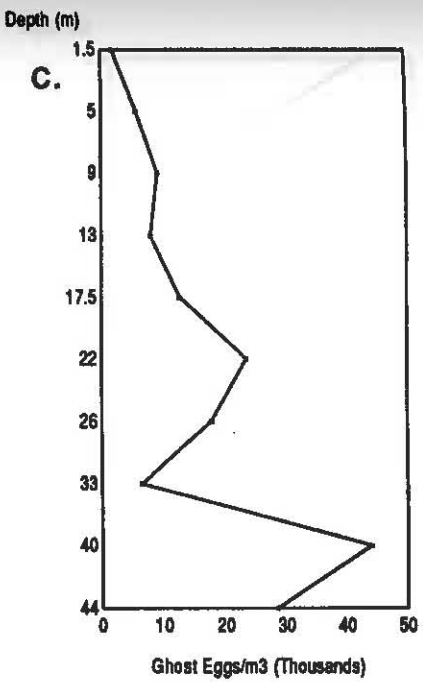
	append	veliger	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
nauplii	-0.893	0.177	0.714	0.536	0.393	0.643	-0.607	-0.607	-0.667
cope	0.464	0.059	-0.286	-0.679	-0.857	-0.464	0.571	0.571	0.505
tint	0.107	0.493	0.107	-0.214	0.071	-0.214	0.025	0.025	0.234
a cili	0.214	0.670	-0.071	-0.426	0.393	-0.464	0.321	0.321	0.487
Proto	-0.393	0.335	0.357	0.500	0.429	0.321	-0.250	-0.250	-0.288
Ceratium	-0.321	0.571	0.393	0.036	0.500	0.071	-0.179	-0.179	-0.054
Gymno	0.571	-0.236	-0.571	-0.143	0.250	-0.464	0.321	0.321	0.450
Dist	0.468	-0.060	-0.613	0.198	0.378	-0.505	0.559	0.559	0.527
Forams	0.089	0.885	0.401	-0.178	0.267	0.089	-0.223	-0.223	0.000

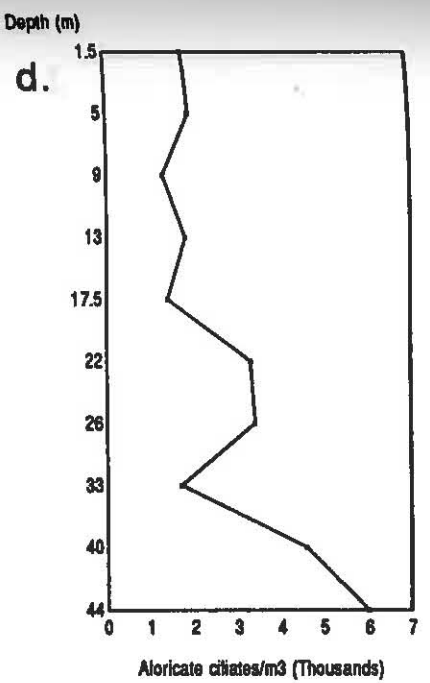
	append	veliger	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
append	1.000								
veliger	0.079	1.000							
egg 2	-0.714	0.512	1.000						
egg 3	-0.571	-0.473	0.179	1.000					
ghost	-0.321	-0.020	0.000	0.536	1.000				
temp	-0.750	0.099	0.857	0.571	0.071	1.000			
salinity	0.714	-0.236	-0.893	-0.464	-0.179	-0.964	1.000		
sigma-t	0.714	-0.236	-0.893	-0.464	-0.179	-0.964	1.000	1.000	
chl a	0.811	-0.010	-0.829	-0.613	-0.126	-0.991	0.955	0.955	1.000

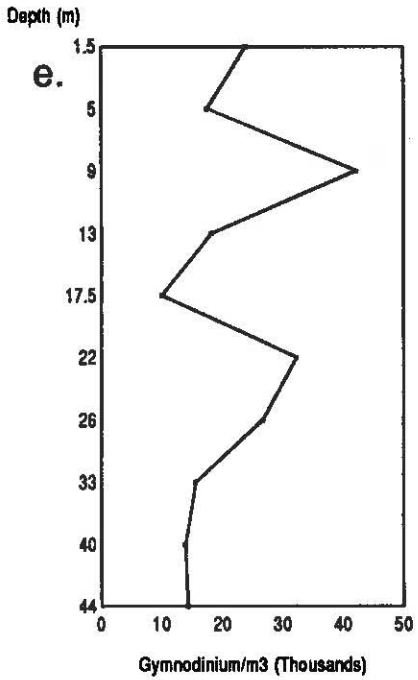
Figure 10. Vertical distributions of the taxonomic groups at site C. Depths indicate the center of each sampling range.

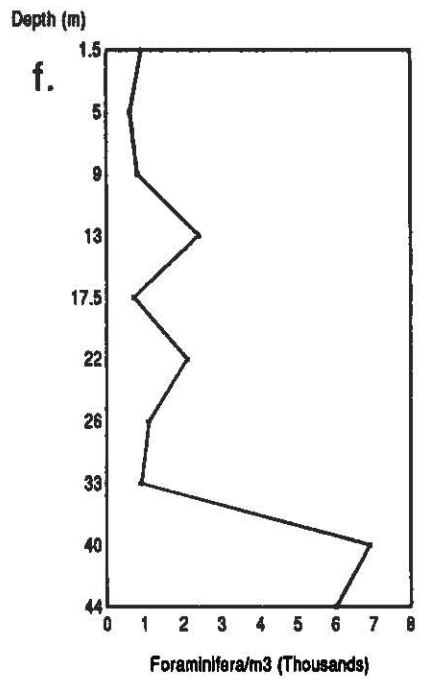

Depth (m)
a.
1.5
5
9
13
17.5
22
26
33
40
44
0
1
2
3
4
5
Protoperidinium/m3 (Thousands)

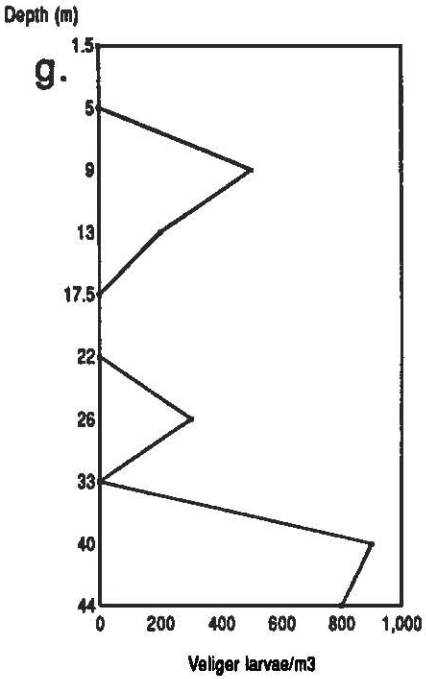

Depth (m)
b.
1.5
5
9
13
17.5
22
26
33
40
44
0
500
1,000
1,500
2,000
Ceratium/m3

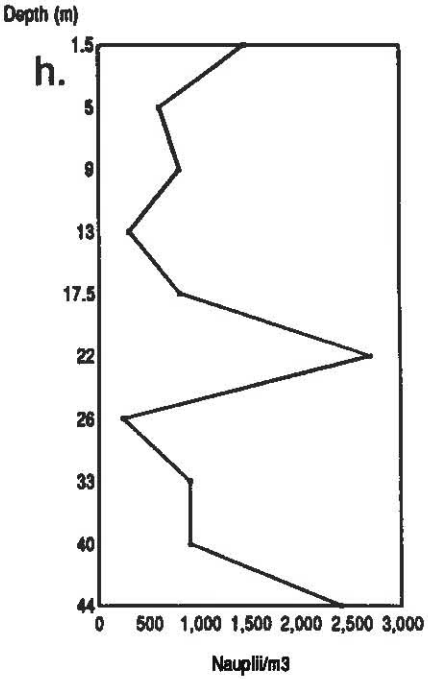

Depth (m)
c.
1.5
5
9
13
17.5
22
26
33
40
44
0
10
20
30
40
50
Ghost Eggs/m3 (Thousands)

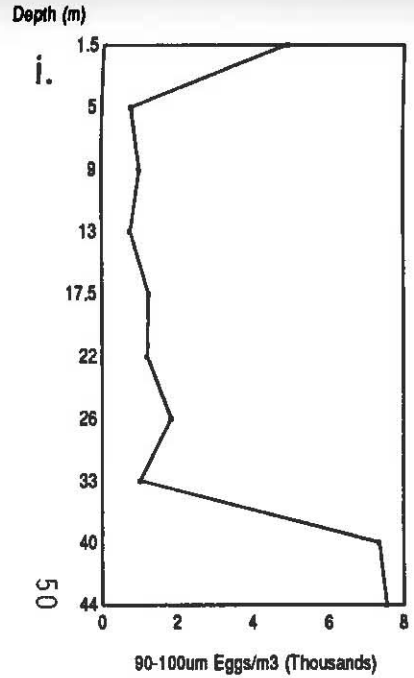

Depth (m)
d.
1.5
5
9
13
17.5
22
26
33
40
44
0
1
2
3
4
5
6
7
Aloricate ciliates/m3 (Thousands)

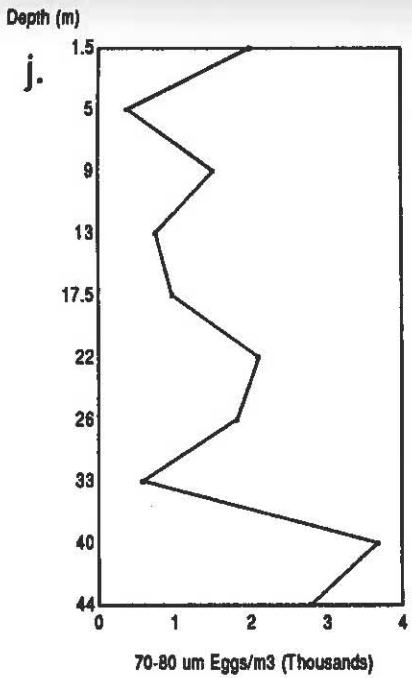

Depth (m)
e.
1.5
5
9
13
17.5
22
26
33
40
44
0
10
20
30
40
50
Gymnodinium/m3 (Thousands)

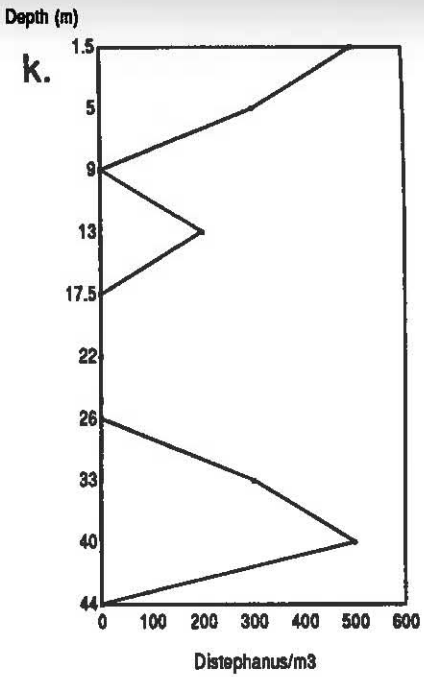

Depth (m)
f.
1.5
5
9
13
17.5
22
26
33
40
44
0
1
2
3
4
5
6
7
8
Foraminifera/m3 (Thousands)

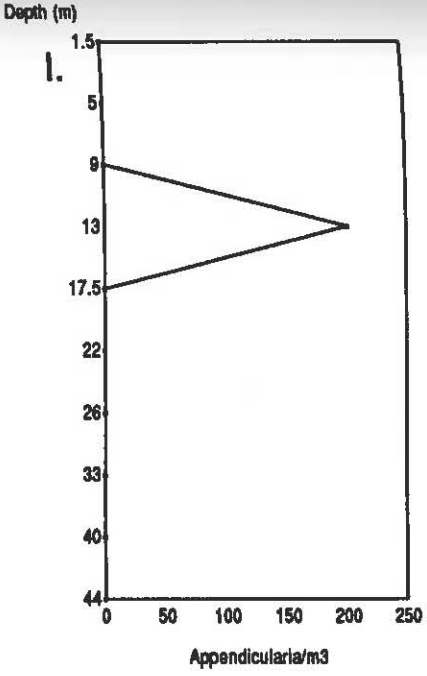

Depth (m)
g.
1.5
5
9
13
17.5
22
26
33
40
44
0
200
400
600
800
1,000
Veliger larvae/m3

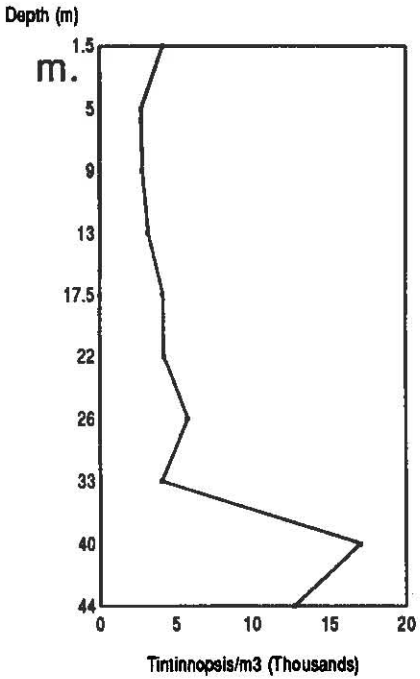

Depth (m)
h.
1.5
5
9
13
17.5
22
26
33
40
44
0
500
1,000
1,500
2,000
2,500
3,000
Naupli/m3

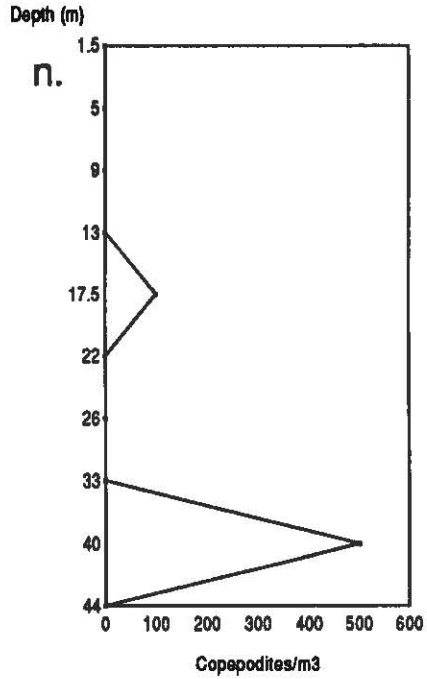

Depth (m)
i.
1.5
5
9
13
17.5
22
26
33
40
44
0
2
4
6
8
90-100um Eggs/m3 (Thousands)

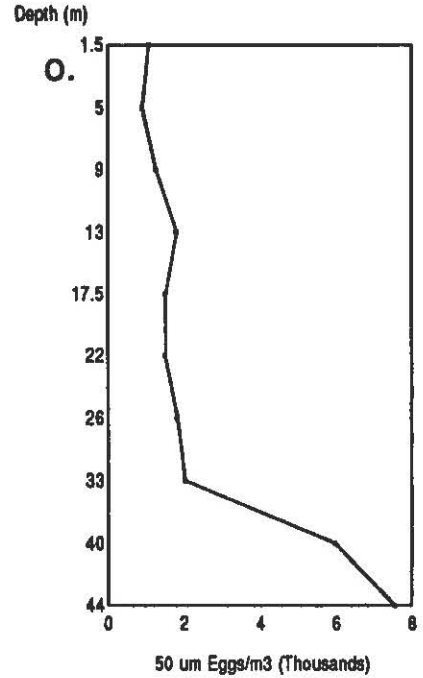

Depth (m)
j.
1.5
5
9
13
17.5
22
26
33
40
44
0
1
2
3
4
70-80 um Eggs/m3 (Thousands)


Depth (m)
k.
1.5
5
9
13
17.5
22
26
33
40
44
0
100
200
300
400
500
600
Distephanus/m3


Depth (m)
l.
1.5
5
9
13
17.5
22
26
33
40
44
0
50
100
150
200
250
Appendicularia/m3


Depth (m)
m.
1.5
5
9
13
17.5
22
26
33
40
44
0
5
10
15
20
Tintinnopsis/m3 (Thousands)


Depth (m)
n.
1.5
5
9
13
17.5
22
26
33
40
44
0
100
200
300
400
500
600
Copepodites/m3


Depth (m)
o.
1.5
5
9
13
17.5
22
26
33
40
44
0
2
4
6
8
50 um Eggs/m3 (Thousands)

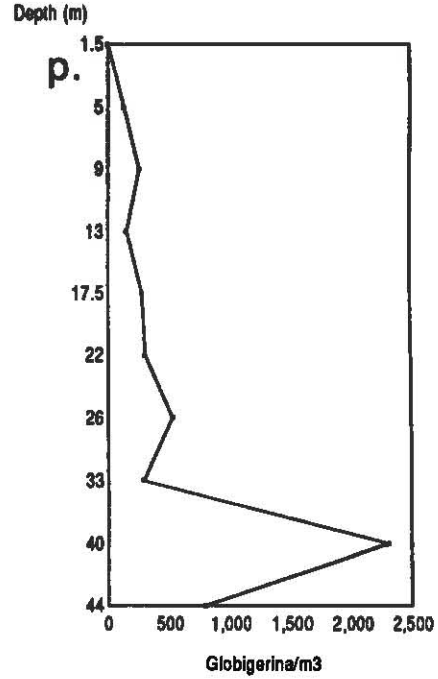
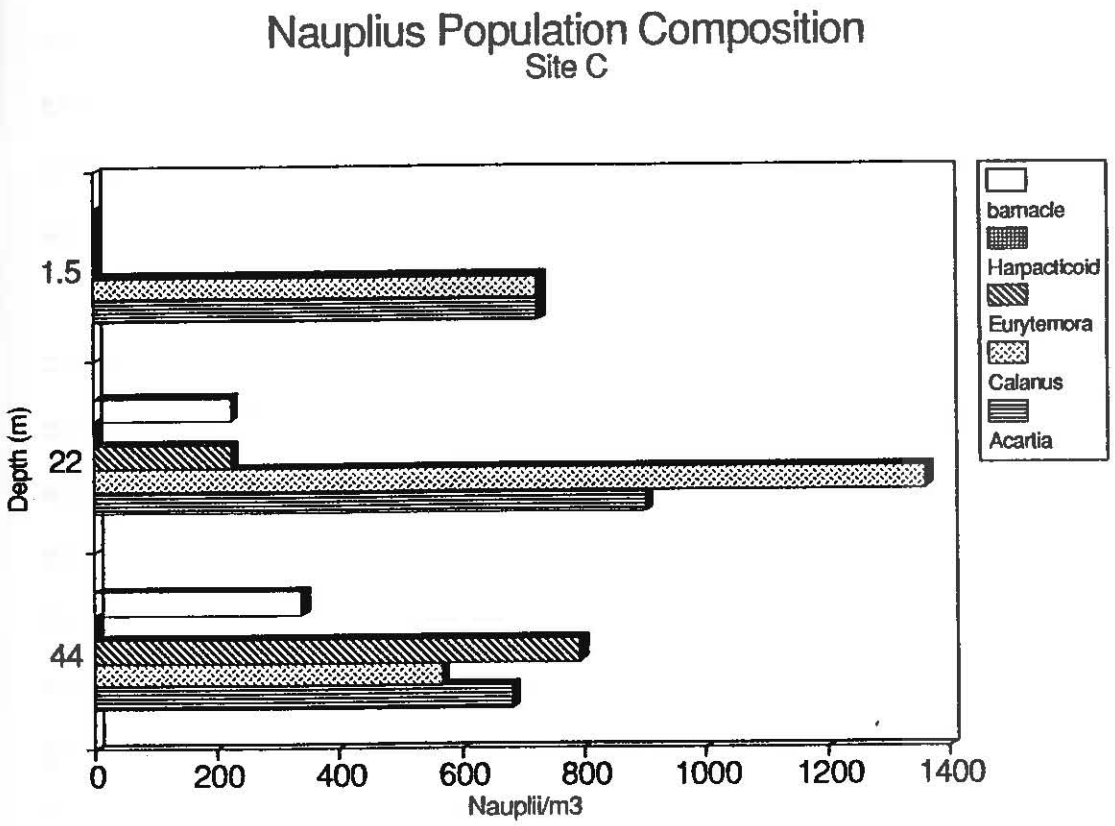

Depth (m)
p.
1.5
5
9
13
17.5
22
26
33
40
44
0
500
1,000
1,500
2,000
2,500
Globigerina/m3

Figure 11. Composition of the copepod nauplius populations in three samples at site C. Depths indicate the center of each sampling range.


Nauplius Population Composition
Site C
Depth (m)
1.5
22
44
0
200
400
600
800
1000
1200
1400
Nauplii/m3
barnacle
Harpacticoid
Eurytemora
Calanus
Acartia

22-24 m; both increased at 42-46 m where *Eurytemora* was the most abundant nauplius genus.

Seventeen species of diatoms were detected in the surface phytoplankton community (Table 4). By comparison to site A, there was an increase in the number of smaller centric species (i.e. *Chaetoceros teres* and *Fragilaria oceanica*) as well as pennate species (*Pleurosigma* sp.), while the number of larger centric species decreased.

Spearman Rank Order Correlation Coefficients indicate that temperature was negatively correlated with salinity and sigma-t while salinity and sigma-t were positively correlated (Table 6). The only significant correlation between microzooplankton and physical environmental variables at this station occurred between Foraminifera abundance and temperature (r_s=0.71; $p<0.05$) and sigma-t (r_s=-0.68, $p<0.05$). Chlorophyll concentration was positively and significantly correlated with abundances of copepod nauplii, *Tintinnopsis* spp., *Protoperidinium* spp., *Globigerina* sp., 70-80 um eggs, 90-100 um eggs and ghost eggs (empty egg cases).

Site D: Central channel

Nineteen depth intervals were sampled by LHPR between the surface and 85 m (Table 2). The water column at this site was isothermal, while the distributions of the sixteen taxonomic groups were not homogeneous. *Protoperidinium* spp., Foraminifera, copepod nauplii, 90-100 um eggs and copepodites (Figures 12 a,f,h,i,n) were concentrated in

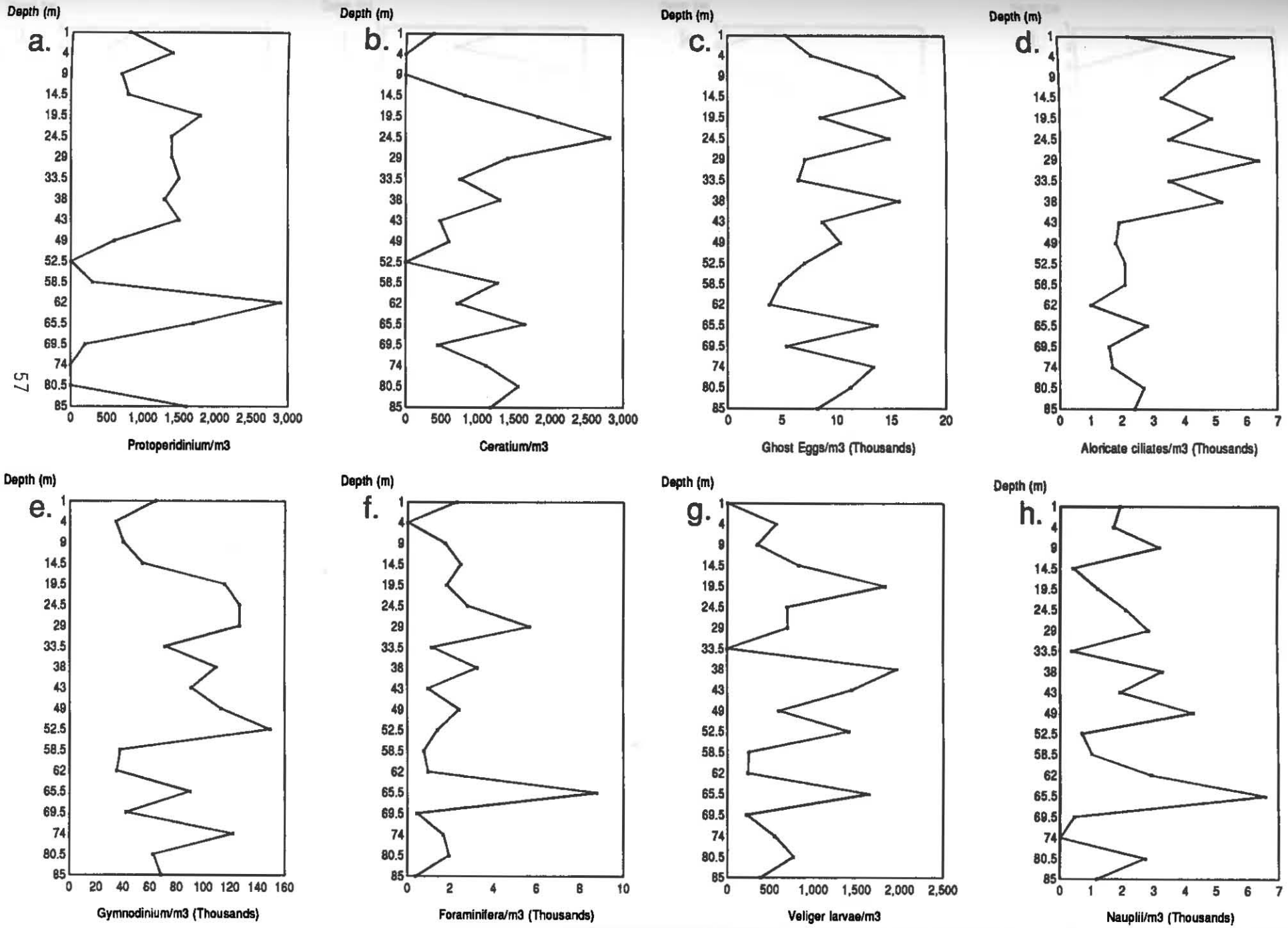
Table 6. Spearman rank order correlation coefficients for site C (n=10; $p<0.05=0.648$). Abbreviations are the same as in Table 5.

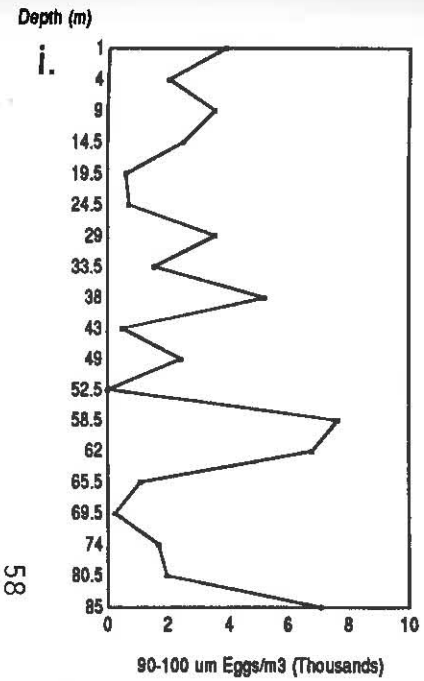
	nauplii	cope	tint	a cili	Proto	Ceratium	Gymno	Dist	Forams	Globi
nauplii	1.000									
cope	-0.069	1.000								
tint	0.794	0.389	1.000							
a cili	0.564	0.061	0.721	1.000						
Proto	0.794	0.199	0.855	0.661	1.000					
Ceratium	0.479	0.078	0.661	0.818	0.721	1.000				
Gymno	0.115	-0.683	-0.273	-0.188	-0.091	-0.067	1.000			
Dist	-0.213	0.148	-0.032	-0.019	-0.200	0.317	-0.239	1.000		
Forams	0.467	0.156	0.758	0.721	0.612	0.636	-0.103	0.071	1.000	
Globi	0.588	0.389	0.794	0.648	-0.522	0.370	-0.297	-0.304	0.636	1.000

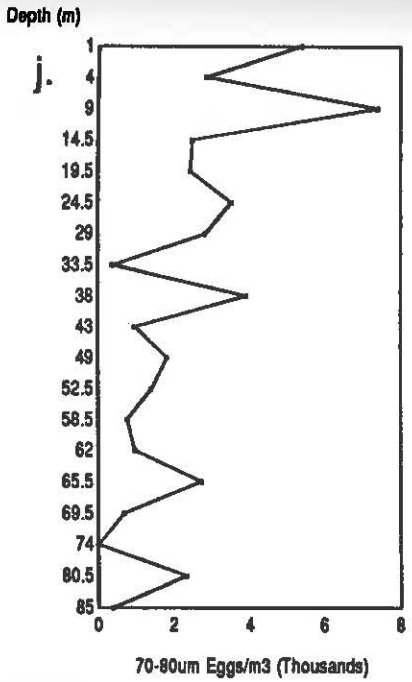
	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
nauplii	-0.522	0.175	0.345	-0.067	0.117	-0.083	0.191	-0.261	-0.252	0.816
cope	-0.166	0.249	0.294	0.525	0.456	0.525	0.272	0.000	-0.088	0.319
tint	-0.290	0.562	0.673	0.083	0.367	0.117	0.464	-0.389	-0.423	0.822
a cili	-0.058	0.575	0.527	0.050	0.433	0.033	0.356	-0.450	-0.411	0.500
Proto	-0.522	0.550	0.394	-0.267	-0.117	-0.300	0.191	-0.255	-0.264	0.717
Ceratium	-0.174	0.588	0.273	-0.350	0.000	-0.383	0.114	-0.353	-0.288	0.441
Gymno	0.058	-0.097	-0.491	-0.667	-0.567	-0.650	-0.337	0.085	0.092	-0.132
Dist	0.062	-0.159	-0.097	0.104	0.261	0.087	0.216	0.104	0.216	-0.182
Forams	0.290	0.679	0.697	0.033	0.500	0.150	0.712	-0.638	-0.681	0.592
Globi	-0.290	0.666	0.830	0.483	0.567	0.500	0.432	-0.073	-0.178	0.776

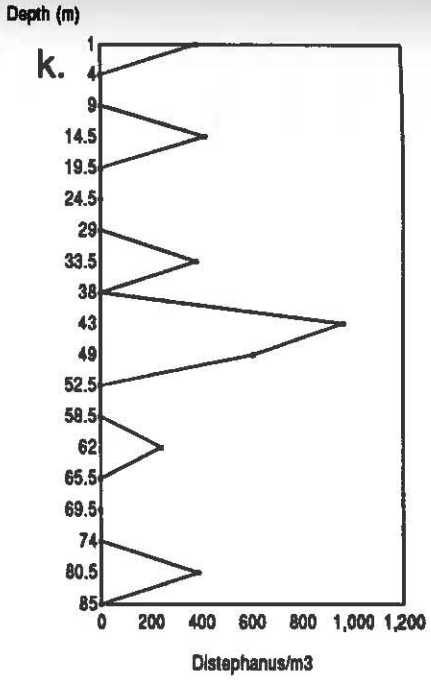
	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
append	1.000									
veliger	0.062	1.000								
egg 1	0.058	0.653	1.000							
egg 2	-0.137	-0.146	0.533	1.000						
egg 3	0.137	0.018	0.683	0.850	1.000					
ghost	0.000	-0.091	0.617	0.983	0.883	1.000				
temp	0.487	0.386	0.591	0.275	0.514	0.417	1.000			
salinity	-0.524	-0.169	-0.188	0.226	-0.167	0.126	-0.803	1.000		
sigma-t	-0.529	-0.268	-0.276	0.153	-0.203	0.034	-0.888	0.979	1.000	
chl a	-0.504	0.507	0.526	0.875	0.763	0.783	0.411	-0.224	-0.300	1.000

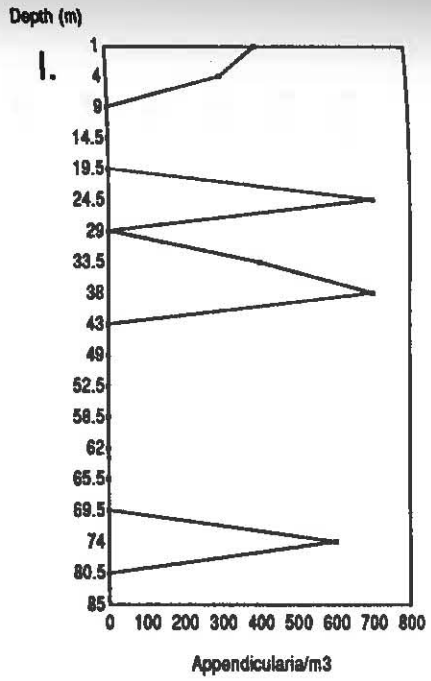
Figure 12. Vertical distributions of the taxonomic groups at site D. Depths indicate the center of each sampling range.

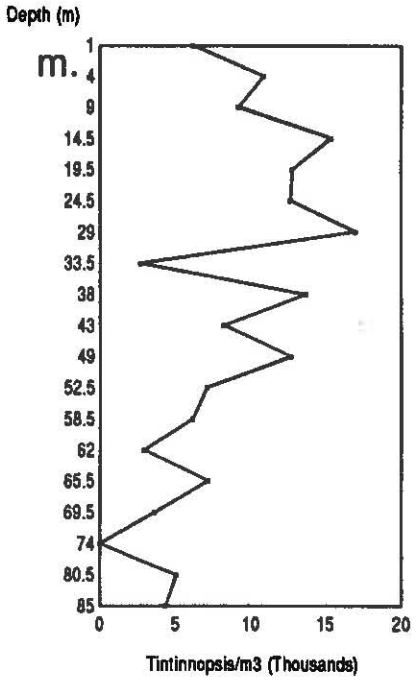

Depth (m)
a.
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0 500 1,000 1,500 2,000 2,500 3,000
Protoperidinium/m3
Depth (m)
b.
0 500 1,000 1,500 2,000 2,500 3,000
Ceratium/m3
Depth (m)
c.
0 5 10 15 20
Ghost Eggs/m3 (Thousands)
Depth (m)
d.
0 1 2 3 4 5 6 7
Aloricate ciliates/m3 (Thousands)
Depth (m)
e.
0 20 40 60 80 100 120 140 160
Gymnodinium/m3 (Thousands)
Depth (m)
f.
0 2 4 6 8 10
Foraminifera/m3 (Thousands)
Depth (m)
g.
0 500 1,000 1,500 2,000 2,500
Veliger larvae/m3
Depth (m)
h.
0 1 2 3 4 5 6 7
Nauplii/m3 (Thousands)

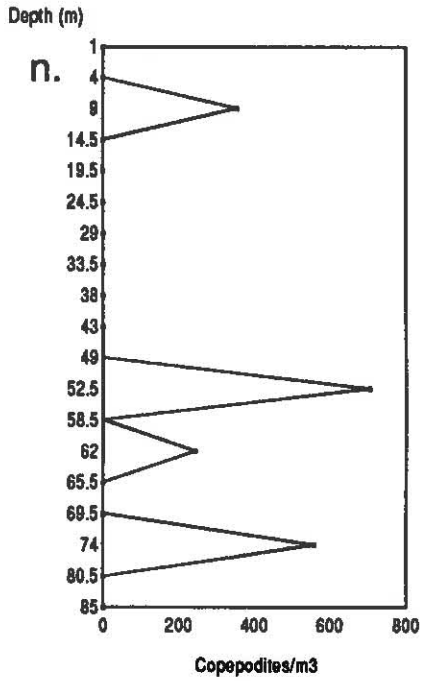

i.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
2
4
6
8
10
90-100 um Eggs/m3 (Thousands)

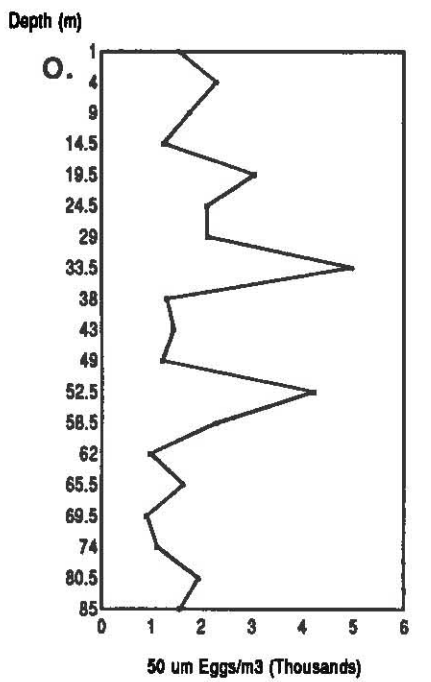

j.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
2
4
6
8
70-80um Eggs/m3 (Thousands)

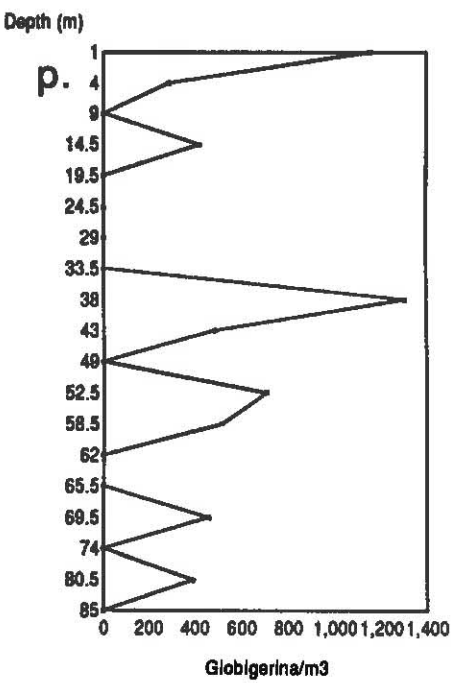

k.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
200
400
600
800
1,000
1,200
Distephanus/m3


l.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
100
200
300
400
500
600
700
800
Appendicularia/m3


m.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
5
10
15
20
Tintinnopsis/m3 (Thousands)


n.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
200
400
600
800
Copepodites/m3


o.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
1
2
3
4
5
6
50 um Eggs/m3 (Thousands)


p.
Depth (m)
1
4
9
14.5
19.5
24.5
29
33.5
38
43
49
52.5
58.5
62
65.5
69.5
74
80.5
85
0
200
400
600
800
1,000
1,200
1,400
Globigerina/m3

the lower third of the water column (below 60 m). The highest abundances of copepod nauplii and Foraminifera were detected in the 64-67 m sample. *Protoperidinium* spp. was most abundant at 60-64 m. Seventy-80 um eggs (Figure 12 j) were concentrated in the upper 31 m. The *Ceratium* spp., aloricate ciliates, Appendicularia and *Tintinnopsis* spp. (Figures 12 b,d,l,m) were also concentrated in the upper half of the water column. Ghost eggs were distributed throughout the water column (Figure 12 c). Peak abundances of the remaining groups were detected in the mid-water column (Figures 12 e,g,k,o,p).

Samples from 0-2 m, 36-40 m and 64-67 m were examined to determine the composition of the copepod nauplius population. At this site, as with the two previous sites, abundances of nauplius genera varied with depth (Figure 13). *Eurytemora*, *Calanus* and barnacle nauplii all increased in abundance with depth. *Acartia* occurred only at 0-3 m, dominating this sample with about equal numbers of *Eurytemora*. At 36-40 m, *Eurytemora* dominated, followed by barnacle nauplii and similar low numbers of harpacticoid and *Calanus*. *Eurytemora* again dominated at 64-67 m followed by *Calanus* and barnacle nauplii.

The lowest chlorophyll concentrations detected along the transect were at this site. The number of diatom species detected at the surface dropped from 17 at site C to 13, more than half of which were pennate (Table 4).

Spearman Rank Order correlation coefficients for site D are presented in Table 7. Temperature, salinity and sigma-t

Figure 13. Composition of copepod nauplius populations in three samples at site D. Depths indicate the center of each sampling range.

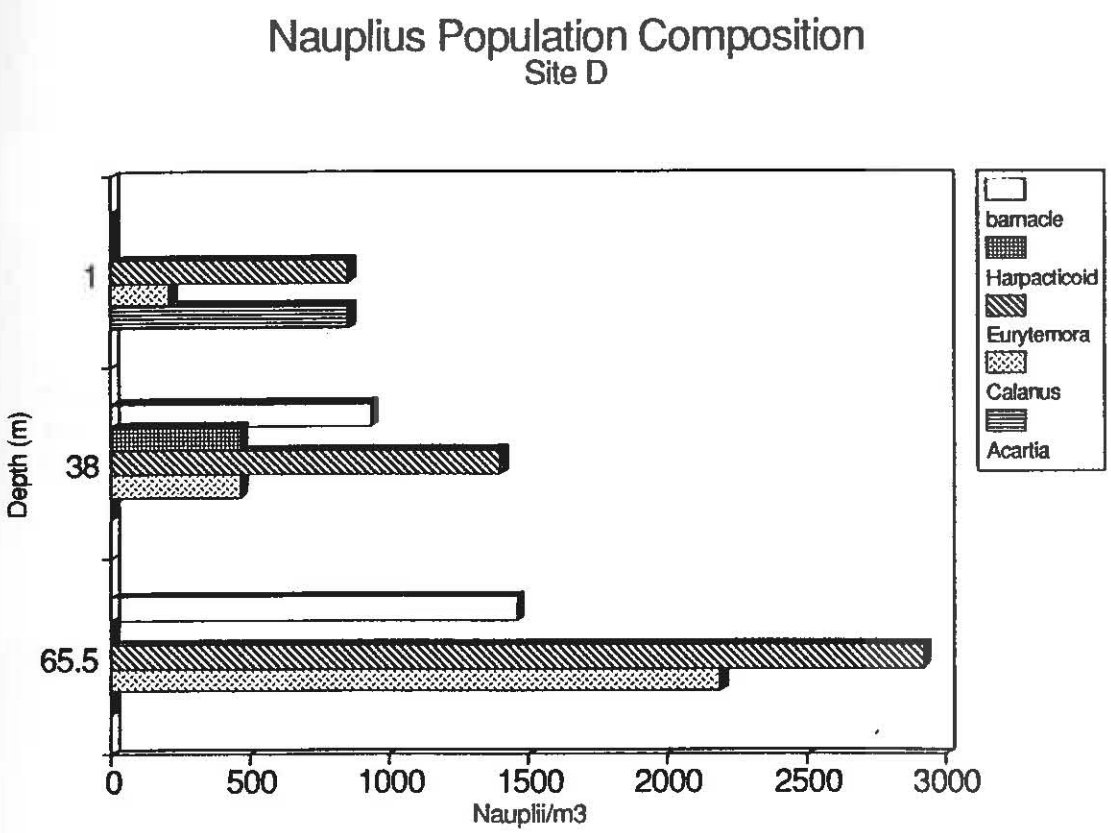

Nauplius Population Composition
Site D
Depth (m)
1
38
65.5
0
500
1000
1500
2000
2500
3000
Nauplii/m3
barnacle
Harpacticoid
Eurytemora
Calanus
Acartia

Table 7. Spearman rank order correlation coefficients for site D (n=19; $p<0.05=0.46$). Abbreviations are the same as in Table 5.

	nauplii	cope	tint	a cili	Proto	Ceratium	Gymno	Dist	Forams	Globi
nauplii	1.000									
cope	-0.125	1.000								
tint	0.420	-0.342	1.000							
a cili	0.215	-0.320	0.651	1.000						
Proto	0.251	-0.303	0.146	0.295	1.000					
Ceratium	0.181	-0.409	0.207	0.295	0.268	1.000				
Gymno	0.022	0.101	0.293	0.147	-0.084	0.366	1.000			
Dist	0.061	-0.230	-0.013	-0.331	-0.007	-0.201	-0.139	1.000		
Forams	0.520	-0.157	0.575	0.147	0.000	0.517	0.507	0.065	1.000	
Globi	-0.158	-0.118	0.067	-0.120	-0.429	-0.317	-0.146	0.145	-0.114	1.000

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
nauplii	-0.118	0.314	-0.148	0.611	0.249	0.252	-0.040	-0.034	-0.020	-0.002
cope	-0.042	-0.121	-0.091	-0.135	-0.089	-0.058	-0.199	-0.304	-0.253	-0.221
tint	-0.055	0.632	0.144	0.689	0.033	0.509	0.547	0.510	0.326	0.064
a cili	0.249	0.375	0.570	0.639	0.079	0.389	0.619	0.454	0.168	0.036
Proto	-0.053	0.120	0.118	0.072	0.121	-0.073	0.315	0.361	0.381	0.147
Ceratium	0.094	0.432	0.158	0.021	0.053	0.344	-0.228	-0.087	-0.131	-0.474
Gymno	0.204	0.505	0.195	-0.014	-0.425	0.276	-0.026	0.032	-0.131	-0.241
Dist	-0.155	-0.060	-0.287	-0.105	0.002	-0.011	0.019	0.104	0.147	0.311
Forams	0.168	0.491	-0.037	0.574	0.005	0.598	0.117	0.234	0.093	-0.317
Globi	0.099	0.117	-0.049	0.138	0.016	-0.147	0.040	-0.129	0.065	0.383

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
append	1.000									
veliger	-0.129	1.000								
egg 1	0.023	0.120	1.000							
egg 2	0.217	0.286	0.121	1.000						
egg 3	0.015	-0.318	-0.161	0.165	1.000					
ghost	0.216	0.598	-0.166	0.422	-0.110	1.000				
temp	0.331	-0.064	0.323	0.644	0.172	0.130	1.000			
salinity	0.129	-0.057	0.341	0.486	0.869	0.013	0.825	1.000		
sigma-t	-0.089	0.021	0.244	0.273	0.145	-0.184	0.522	0.841	1.000	
chl a	0.204	-0.062	0.008	0.216	-0.076	-0.192	0.445	0.277	0.307	1.000

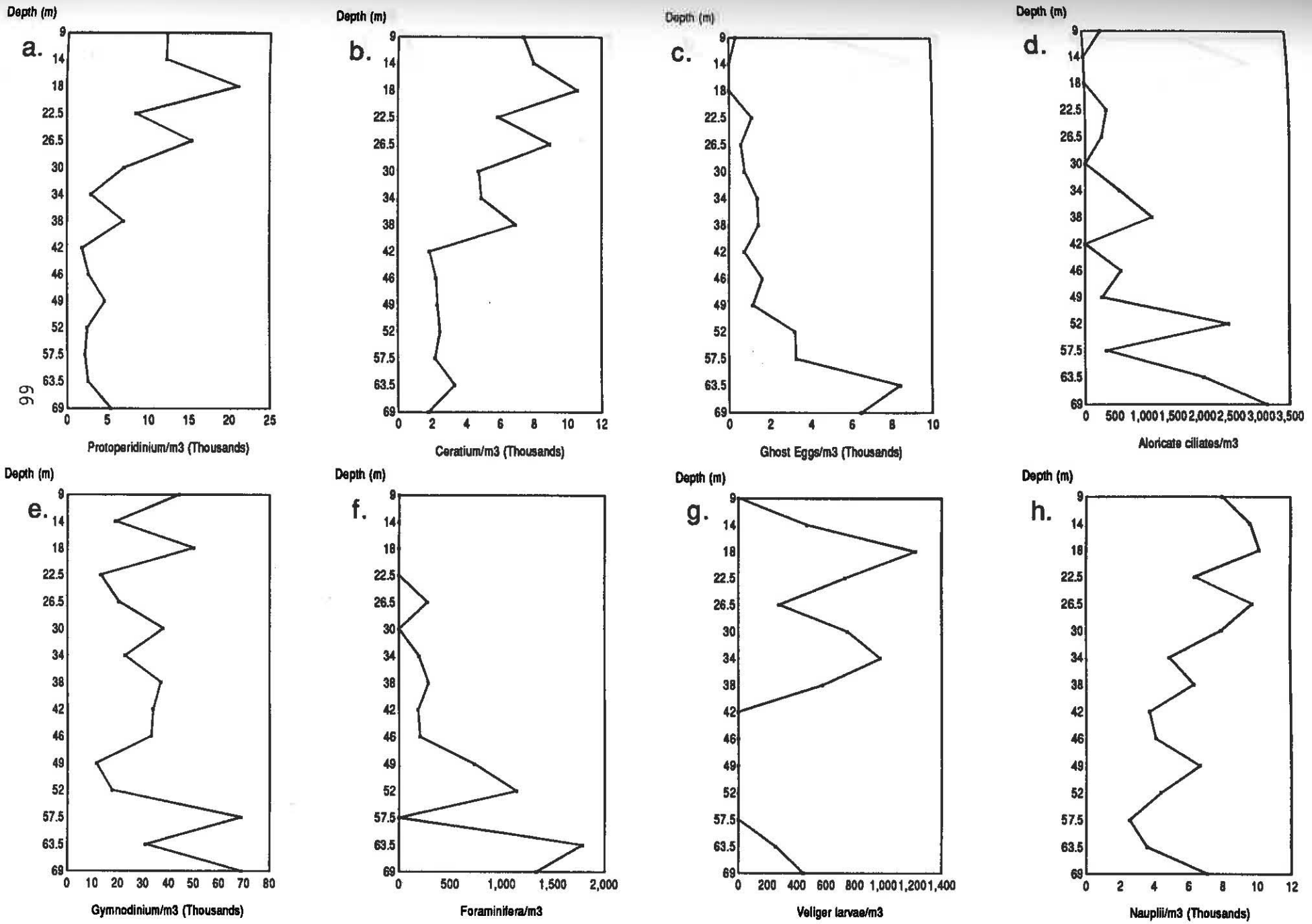
distributions all covaried. The abundances of 70-80 um eggs and *Tintinnopsis* spp. varied directly with temperature and salinity. Chlorophyll concentration was not correlated with any physical environmental variable. The abundance of 90-100 um eggs was positively correlated with sigma-t. The positive correlation between the abundance of copepod nauplii and that of 70-80 um eggs was significant, while the correlation between the abundances of nauplii and 90-100 um eggs was not.

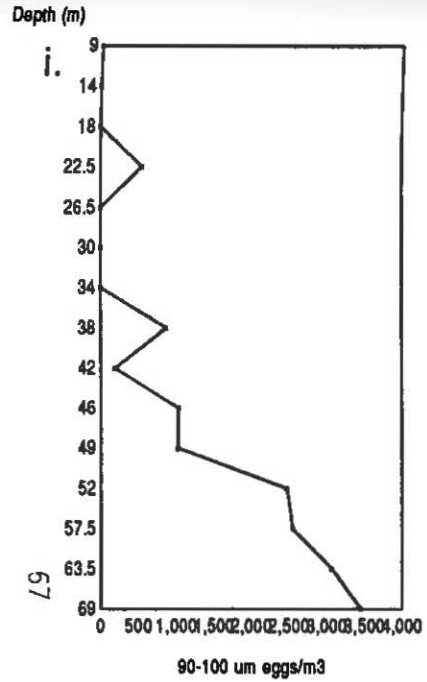
Site F: Offshore stratified region

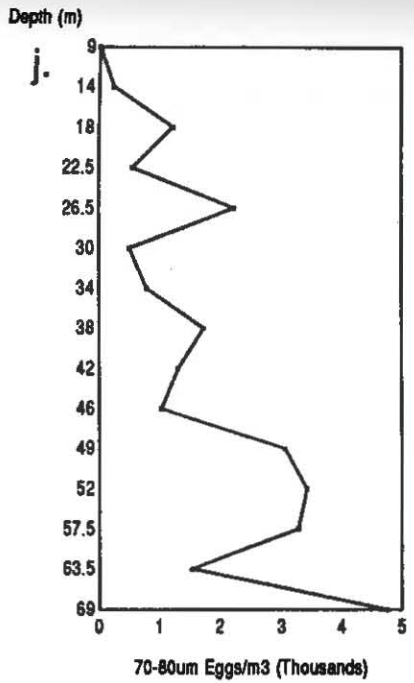
Fifteen depth intervals were sampled by LHPR between 6 and 72 m (Table 2). Distributions of 13 of 16 taxonomic groups strongly reflected water column stratification at this site, which had thermoclines at approximately 32 m and 57 m. *Protoperidinium* spp., *Ceratium* spp., veliger larvae, copepod nauplii, *Distephanus* sp., copepodites and *Globigerina* sp. were more abundant above than below 40 m (Figure 14 a,b,g,h,k,n,p). *Distephanus* sp. was only found above 40 m.

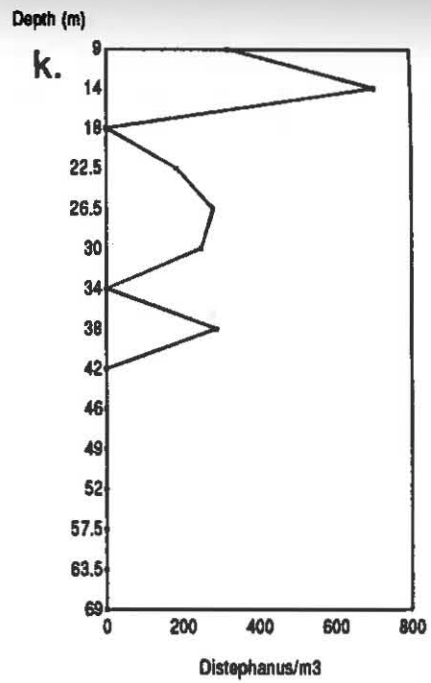
Ghost eggs, aloricate ciliates, Foraminifera, 90-100 um eggs, 70-80 um eggs, and 50 um eggs were among the groups that were more abundant below, than above, 40 m (Figures 14 c,d,f,i,j,o). Ninety-100 um egg abundances were strongly associated with the bottom mixed layer; these eggs were only detected in two samples collected above 40 m. The abundances of *Gymnodinium* sp., Appendicularia and *Tintinnopsis* spp. were not associated with a particular depth range (Figure 14 e,l,m).

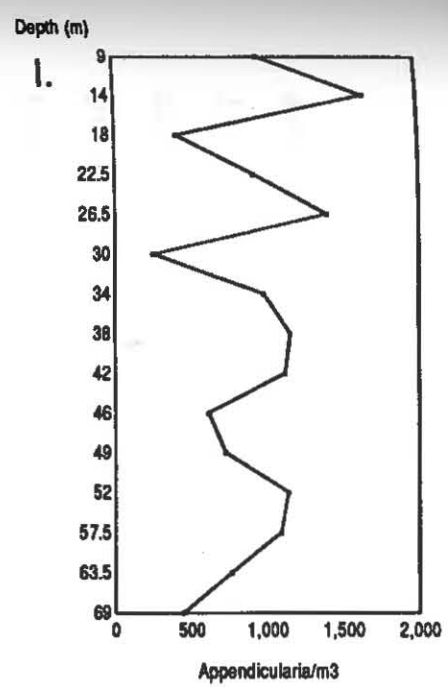
Figure 14. Vertical distributions of the taxonomic groups at site F. Depths indicate the center of each sampling range.

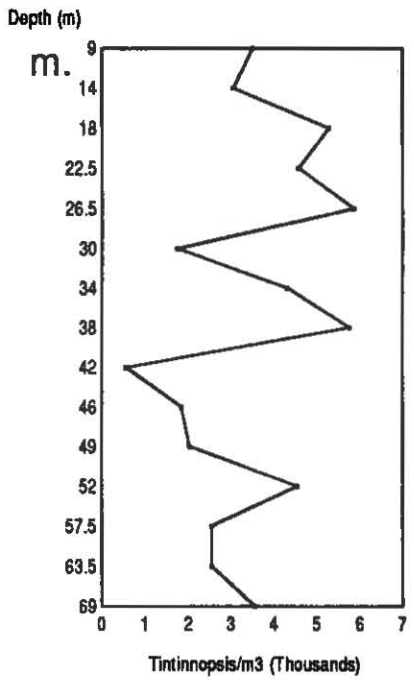

a.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 5 10 15 20 25
Protoperidinium/m3 (Thousands)
b.
Depth (m)
0 2 4 6 8 10 12
Ceratium/m3 (Thousands)
c.
Depth (m)
0 2 4 6 8 10
Ghost Eggs/m3 (Thousands)
d.
Depth (m)
0 500 1,000 1,500 2,000 2,500 3,000 3,500
Aloricate ciliates/m3
e.
Depth (m)
0 10 20 30 40 50 60 70 80
Gymnodinium/m3 (Thousands)
f.
Depth (m)
0 500 1,000 1,500 2,000
Foraminifera/m3
g.
Depth (m)
0 200 400 600 800 1,000 1,200 1,400
Veliger larvae/m3
h.
Depth (m)
0 2 4 6 8 10 12
Nauplii/m3 (Thousands)

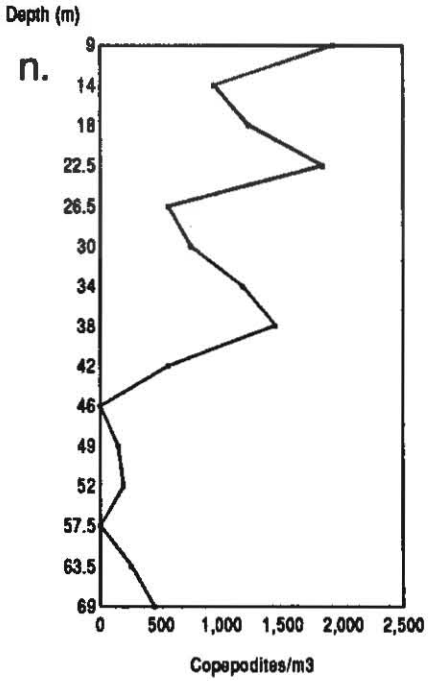

i.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 500 1,000 1,500 2,000 2,500 3,000 3,500 4,000
90-100 um eggs/m3

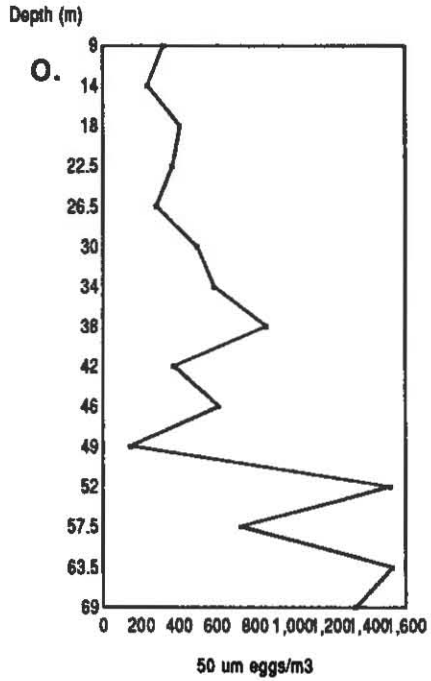

j.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 1 2 3 4 5
70-80um Eggs/m3 (Thousands)

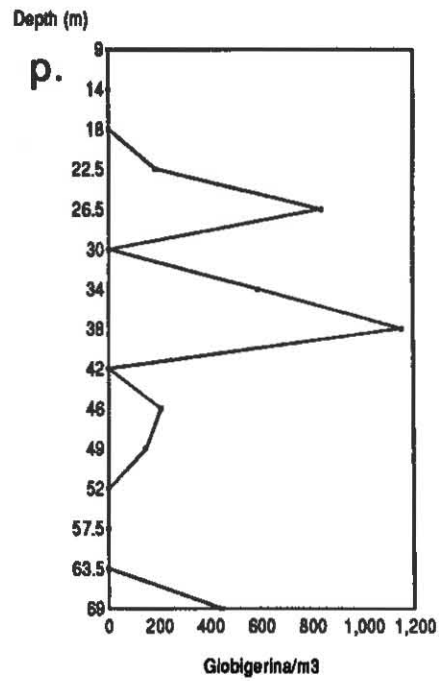

k.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 200 400 600 800
Distephanus/m3


l.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 500 1,000 1,500 2,000
Appendicularia/m3


m.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 1 2 3 4 5 6 7
Tintinnopsis/m3 (Thousands)


n.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 500 1,000 1,500 2,000 2,500
Copepodites/m3


o.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 200 400 600 800 1,000 1,200 1,400 1,600
50 um eggs/m3


p.
Depth (m)
9
14
18
22.5
26.5
30
34
38
42
46
49
52
57.5
63.5
69
0 200 400 600 800 1,000 1,200
Globigerina/m3

Samples from 6-12 m, 16-20 m, 36-40 m and 66-72 m were examined to determine the composition of the nauplius population (Figure 15). *Calanus* nauplii dominated all samples. *Eurytemora*, *Acartia* and harpacticoid nauplii were also present in these samples, but generally in much smaller numbers. Harpacticoid nauplii were abundant only below the thermocline, while *Eurytemora* increased in abundance from the surface to the thermocline and declined below it.

Nineteen species of diatoms were detected in the 6-12 m sample, the largest number detected along the transect (Table 4). The dominant phytoplankter was *Chaetoceros socialis*.

The Spearman Rank Order Correlation Coefficients for site F are presented in Table 8. Temperature was negatively correlated with sigma-t. Salinity and sigma-t covaried. The concentration of chlorophyll was positively correlated with temperature and negatively correlated with sigma-t. The abundances of copepod nauplii, copepodites, *Protoperidinium* spp., and *Ceratium* spp. were positively correlated with temperature and chlorophyll concentration. Aloricate ciliate, Foraminifera, 50 um egg, 70-80 um egg, 90-100 um egg and ghost egg abundances were negatively correlated with temperature and chlorophyll concentration. Copepod nauplii and copepodite abundances were negatively correlated with the abundances of 90-100 um eggs, ghost eggs and aloricate ciliates. The abundances of copepodites and 70-80 um eggs were negatively correlated.

Figure 15. Composition of copepod nauplius populations in four samples at site F. Depths indicate the center of each sampling range.

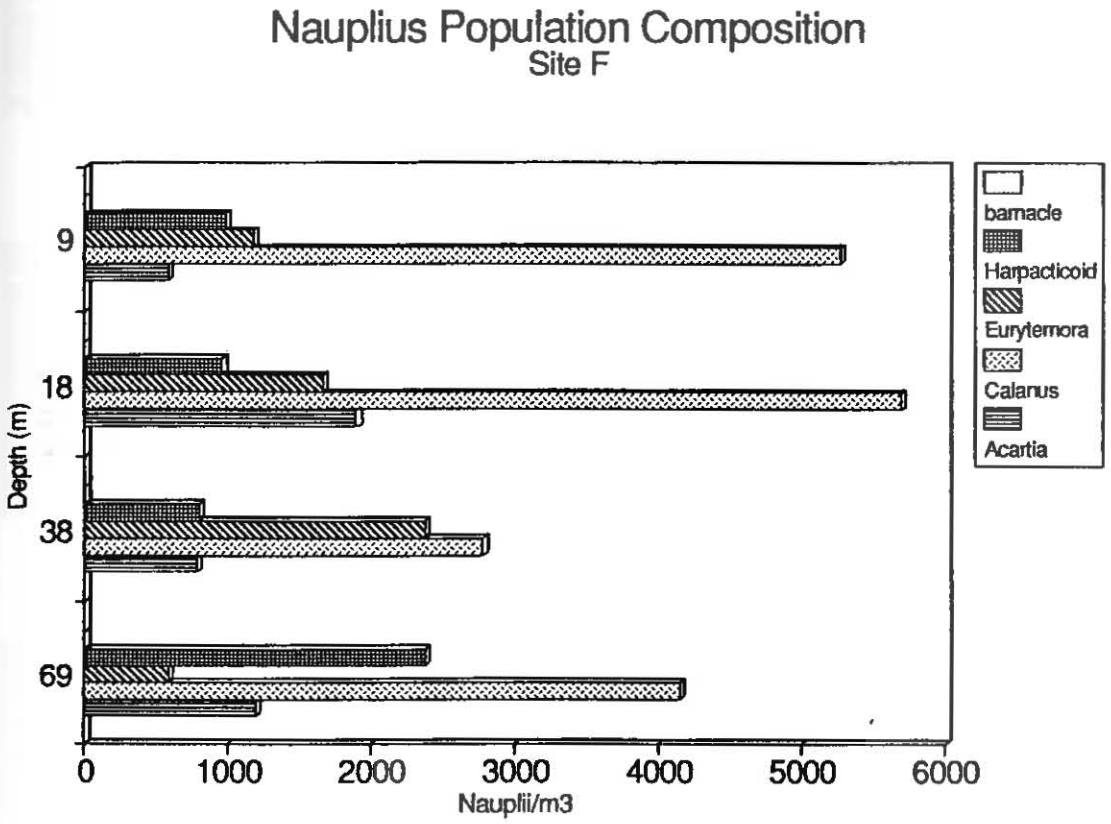

Nauplius Population Composition
Site F
Depth (m)
9
18
38
69
0
1000
2000
3000
4000
5000
6000
Nauplii/m3
barnacle
Harpacticoid
Eurytemora
Calanus
Acartia

Table 8. Spearman rank order correlation coefficients for site F (n=15; $p<0.05=0.521$). Abbreviations are the same as in Table 5.

	nauplii	cope	tint	a cili	Proto	Ceratium	Gymno	Dist	Forams	Globi
nauplii	1.000									
cope	0.517	1.000								
tint	0.432	0.461	1.000							
a cili	-0.479	-0.263	0.247	1.000						
Proto	0.936	0.624	0.546	-0.413	1.000					
Ceratium	0.704	0.674	0.636	-0.400	0.836	1.000				
Gymno	0.018	0.068	-0.104	0.013	0.000	-0.171	1.000			
Dist	0.556	0.613	0.286	-0.329	0.657	0.653	-0.085	1.000		
Forams	-0.314	-0.470	0.109	0.699	-0.389	-0.393	-0.203	-0.404	1.000	
Globi	0.089	0.084	0.486	0.387	0.167	0.062	-0.141	0.090	0.381	1.000

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
nauplii	-0.089	0.480	-0.589	-0.325	-0.658	-0.736	0.732	-0.161	-0.693	0.697
cope	0.097	0.600	-0.309	-0.631	-0.653	-0.594	0.799	-0.295	-0.760	0.743
tint	0.325	0.457	0.043	0.157	-0.183	-0.132	0.301	-0.029	-0.282	0.254
a cili	-0.027	-0.183	0.755	0.497	0.747	-0.848	-0.637	0.232	0.641	-0.594
Proto	-0.054	0.579	-0.539	-0.439	-0.649	-0.697	0.810	-0.238	-0.793	0.728
Ceratium	0.246	0.546	-0.429	-0.511	-0.740	-0.690	0.817	-0.197	-0.761	0.717
Gymno	-0.357	0.090	0.375	0.075	0.098	0.105	-0.050	-0.131	-0.068	-0.196
Dist	0.423	0.223	-0.459	-0.548	-0.566	-0.561	0.696	-0.287	0.709	0.633
Forams	0.024	-0.278	0.503	0.686	0.642	0.668	-0.705	0.205	0.714	-0.592
Globi	0.138	0.250	0.021	0.230	0.042	0.196	-0.034	-0.191	0.012	-0.130

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
append	1.000									
veliger	-0.214	1.000								
egg 1	-0.157	-0.022	1.000							
egg 2	0.075	-0.343	0.457	1.000						
egg 3	-0.153	-0.473	0.669	0.714	1.000					
ghost	-0.155	-0.294	0.813	0.627	0.895	1.000				
temp	0.094	0.471	-0.682	-0.794	-0.894	-0.901	1.000			
salinity	-0.082	0.245	0.415	0.236	0.192	0.391	-0.441	1.000		
sigma-t	-0.100	-0.384	0.668	0.714	0.797	0.878	-0.961	0.616	1.000	
chl a	0.165	0.407	-0.680	-0.752	-0.825	-0.865	0.921	-0.211	-0.836	1.000

Site H: Irish coast

Because only three depth ranges in the upper 14 of 33 m were sampled by LHPR (Table 2), detailed descriptions of vertical distributions were not made at this site.

Calanus nauplii outnumbered every other species by more than two fold in the 0-4 and 4-9 m samples (Figure 16). *Acartia* and *Eurytemora*, harpacticoid and barnacle nauplii occurred in decreasing order of abundance.

Chaetoceros socialis dominated the eight diatom species detected in the surface sample.

In summary, the vertical distributions of microzooplankton were complex during this study. Microzooplankton distributions, as well as associations between the taxonomic groups varied at each site and between sites. Distinct microzooplankton communities could be described in coastal areas and on each side of the fronts. However, clear distinctions were evident of water type, in species composition and in the water column.

Microzooplankton Distributions: Transect Summary

Mean abundances of the 16 most frequently encountered-taxonomic groups varied across the transect (Table 9). Three distinct but overlapping water types were recognized from the taxonomic distribution data. These water types are: (1) the coastal water (sites A, F and H), (2) Welsh coastal water (site A), and (3) the central channel water (sites C, D and F).

The microzooplankton in the coastal water was dominated

Figure 16. Composition of copepod nauplius populations in two samples at site H. Depths indicate the center of each sampling range.

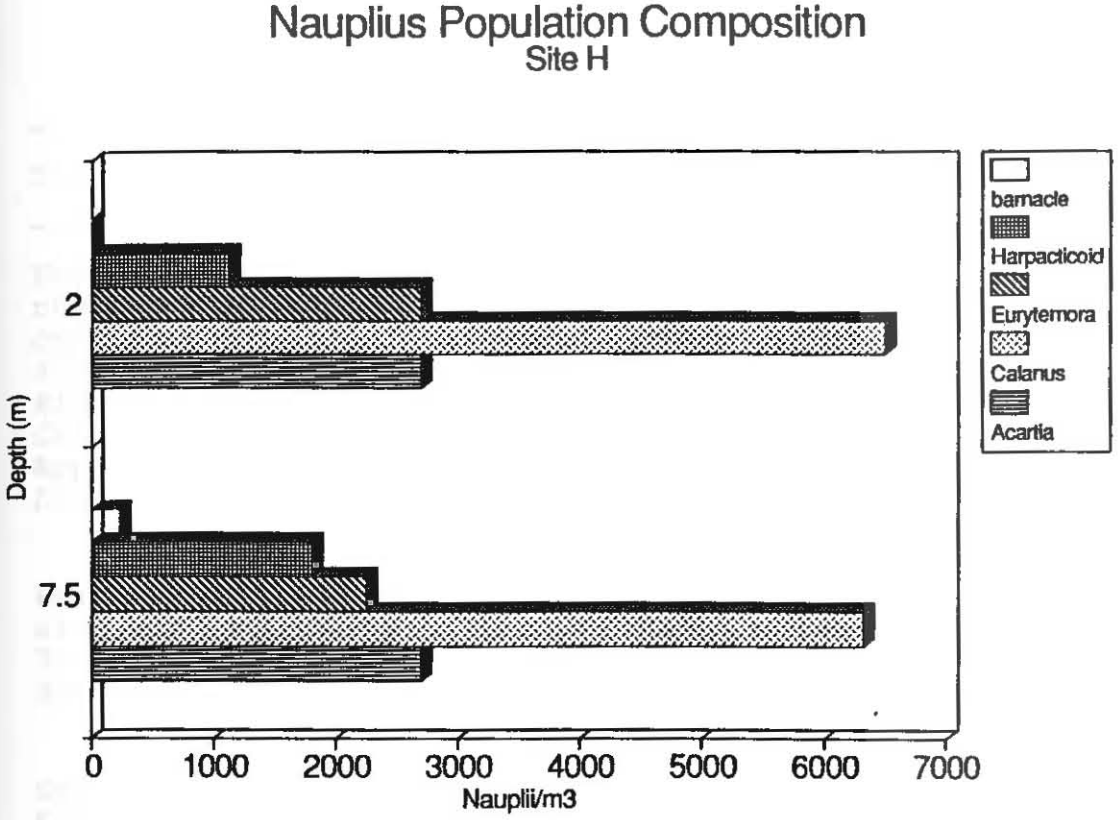

Nauplius Population Composition
Site H
barnacle
Harpacticoid
Eurytemora
Calanus
Acartia
Depth (m)
2
7.5
0
1000
2000
3000
4000
5000
6000
7000
Nauplii/m3

Table 9. Mean abundances of the major taxonomic groups ($x10^3/m^3$).

Taxonomic groups	Sites H	F	D	C	A
Coastal surface water (A, F and H)					
copepod nauplii	13.4	6.4	2.0	1.3	12.2
copepodites	4.9	0.8	0.1	0.06	0.4
Tintinnopsis spp.	11.7	3.5	8.3	6.1	14.2
Protoperidinium spp.	1.9	7.2	1.1	1.5	20.0
Ceratium spp.	3.4	4.9	1.0	0.7	5.3
Appendicularia	0.7	0.9	0.2	0.02	1.7
Distephanus sp.	1.5	0.1	0.2	0.2	0.6
Welsh coastal water (A)					
aloricate ciliates	0	0.8	3.1	2.7	70.5
70-80 um eggs	1.4	1.7	2.3	1.7	6.3
90-100 um eggs	0.3	1.0	2.8	2.8	3.1
Offshore sites (C, D and F)					
Foraminifera	0.1	0.4	2.2	2.2	0.3
Globigerina sp.	0.1	0.2	0.3	0.5	0
veliger larvae	0.3	0.4	0.8	0.2	0.4
50 um eggs	1.2	0.7	2.0	2.5	0
Gymnodinium sp.	27.4	33.9	81.5	21.4	57.6
ghost eggs	1.7	2.0	9.6	15.8	9.1

by copepod nauplii, copepodites, Appendicularia, *Tintinnopsis* spp., *Protoperidinium* spp., and *Ceratium* spp. The highest abundances of these taxa were detected at the coastal sites (sites A and H). Each of these taxa were found in large numbers at site F (stratified region west of the seasonal front), with the exception of *Tintinnopsis* spp. which were more abundant at site D than at site F.

Site A (Welsh coastal water) was east of the Liverpool Bay front. The microzooplankton at this site was dominated by aloricate ciliates. Seventy-80 um eggs and 90-100 um eggs were most abundant at this site.

The microzooplankton in the central channel water (sites C, D and F) contained relatively large numbers of *Globigerina* sp., Foraminifera, 50 um eggs, veliger larvae and ghost eggs. Foraminifera, *Globigerina* sp., 50 um eggs and ghost eggs were abundant at sites C and D, while veliger larvae and *Gymnodinium* sp. were abundant at sites D and F.

Correspondence Analysis

Five factors were extracted by Correspondence Analysis. I will discuss the first three factors, which explain 81% of the variance in the data set. Tables 10 and 11 list the eigenvalues for the data set viewed in two ways, as samples (Table 10) and as taxonomic groups (Table 11). The results are also presented as scatter plots (Figures 17 and 18). The axes have been rotated so that clusters can be easily identified. Corresponding clusters have been circled and numbered on both scatter plots, and the components of each

Table 10. Sample codes and eigenvalues of the first three factors extracted by Correspondence Analysis. The first three factors explain 81% of the variance.

Sites	Code	Depth (m)	Factor 1	Factor 2	Factor 3
A	A1	0-3	0.4561	0.6561	0.6491
	B1	3-9	0.8665	-0.2343	-0.0607
	C1	9-12	0.5523	-0.1442	-0.2572
	D1	12-16	0.977	-0.2276	-0.1376
	E1	16-18	1.0454	-0.2492	-0.076
	F1	18-22	0.9606	-0.2767	-0.0623
	G1	22-26	0.6133	-0.2374	-0.401
C	A2	0-3	-0.2596	-0.0136	0.121
	B2	3-7	-0.3011	-0.2402	0.1619
	C2	7-11	-0.4731	-0.1848	-0.0682
	D2	11-15	-0.4206	-0.4464	0.3417
	E2	15-20	-0.3523	-0.6303	0.8088
	F2	20-24	-0.3673	-0.4743	0.4803
	G2	24-28	-0.2742	-0.3725	0.4825
	H2	28-38	-0.3432	-0.3551	0.3655
	I2	38-42	-0.3887	-0.8291	1.1828
	J2	42-46	-0.2552	-0.6362	1.0166
D	A3	0-2	-0.4083	-0.0626	-0.1009
	B3	2-6	-0.1705	-0.2126	0.1208
	C3	6-12	-0.2683	-0.2674	0.2765
	D3	12-17	-0.3767	-0.2651	0.1758
	E3	17-22	-0.4158	-0.0245	-0.2955
	F3	22-27	-0.4398	-0.0388	-0.2269
	G3	27-31	-0.3999	-0.0409	-0.2468
	H3	31-36	-0.4586	-0.0956	-0.2705
	I3	36-40	-0.4007	-0.1011	-0.0886
	J3	40-46	-0.4618	-0.0032	-0.2811
	K3	46-52	-0.4648	-0.0027	-0.2404
	L3	52-57	-0.5431	-0.0036	-0.4555
	M3	57-60	-0.4104	-0.1546	0.1191
	N3	60-64	-0.3336	0.0412	0.0902
	O3	64-67	-0.421	-0.0813	-0.0475
	P3	67-72	-0.461	-0.1029	-0.2387
	Q3	72-76	-0.56	-0.0617	-0.4079
	R3	76-85	-0.4298	-0.118	-0.0563
	S3	85	-0.446	-0.0802	-0.1469

Table 10. continued

Sites	Code	Depth (m)	Factor 1	Factor 2	Factor 3
F	A4	6-12	0.0584	0.7648	-0.0145
	B4	12-16	0.3595	1.1341	0.3428
	C4	16-20	0.1434	0.84	0.0904
	D4	20-25	0.3237	0.9356	0.4412
	E4	25-28	0.3481	0.9908	0.4217
	F4	28-32	-0.0714	0.6753	-0.0635
	G4	32-36	-0.0312	0.5857	0.1351
	H4	36-40	-0.015	0.5634	0.1131
	I4	40-44	-0.2803	0.4169	-0.2832
	J4	44-48	-0.247	0.3413	-0.1411
	K4	48-50	0.1654	0.6937	0.4363
	L4	50-54	-0.0174	0.1739	0.3432
	M4	54-61	-0.4092	0.1658	-0.316
	N4	61-66	-0.2426	0.0214	0.2357
	O4	66-72	-0.2591	0.1405	-0.0818
H	A5	0-4	0.1829	0.687	0.5131
	B5	4-9	0.062	0.7724	0.2656
	C5	9-14	-0.0187	0.6788	0.144

Table 11. Eigenvalues for taxonomic groups from the Correspondence Analysis, and the percentage of the variance explained by the first three factors.

Taxonomic Group	Factor 1	Factor 2	Factor 3
copepod nauplii	0.362	0.7807	0.3852
copepodites	0.7752	0.6854	0.2603
Protoperidinium spp.	0.7347	0.5992	0.2798
Ceratium spp.	0.3637	0.8845	0.3346
Appendicularia	0.5174	0.613	0.0145
Distephanus sp.	0.2326	0.6186	0.3609
Tintinnopsis spp.	0.0032	-0.0254	0.3342
70-80 um eggs	0.1617	-0.0464	0.3052
Gymnodinium sp.	-0.3233	0.0479	-0.2593
veliger larvae	-0.2852	0.1444	0.0601
Foraminifera	-0.6148	-0.5328	0.5479
Globigerina	-0.5068	-0.217	0.8738
50 um eggs	-0.6412	-0.467	0.5677
90-100 um eggs	-0.2791	-0.2499	0.5781
ghost eggs	-0.3499	-0.6198	0.6412
aloricate ciliates	1.227	-0.5469	-0.2686
Percent variance	42	22	17

Figure 17. The relationships between the samples plotted on the first three factors extracted by Correspondence Analysis. The first three factors explain 81% of the variation in the data set. The clusters have been circled and numbered for easier identification. Cluster #1 contains the samples from station 259 (0-3 m), station 273 (6-40 m, 46-52m), station 278 (0-14 m); cluster #2 contains samples from station 273 (40-72 m), station 267 and station 264; cluster #3 contains samples from station 259 (3-26 m). The codes representing the samples are listed in Table 10.

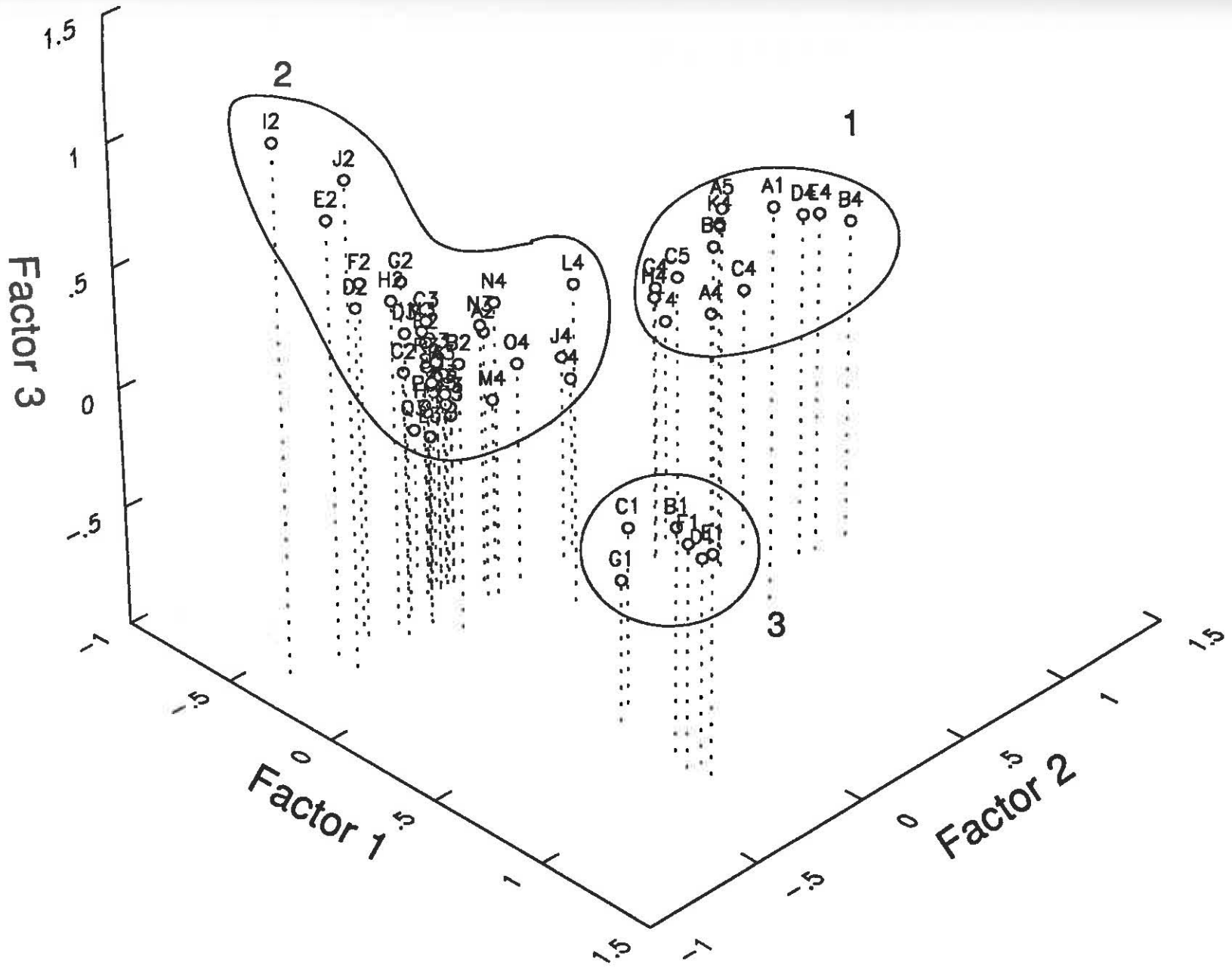
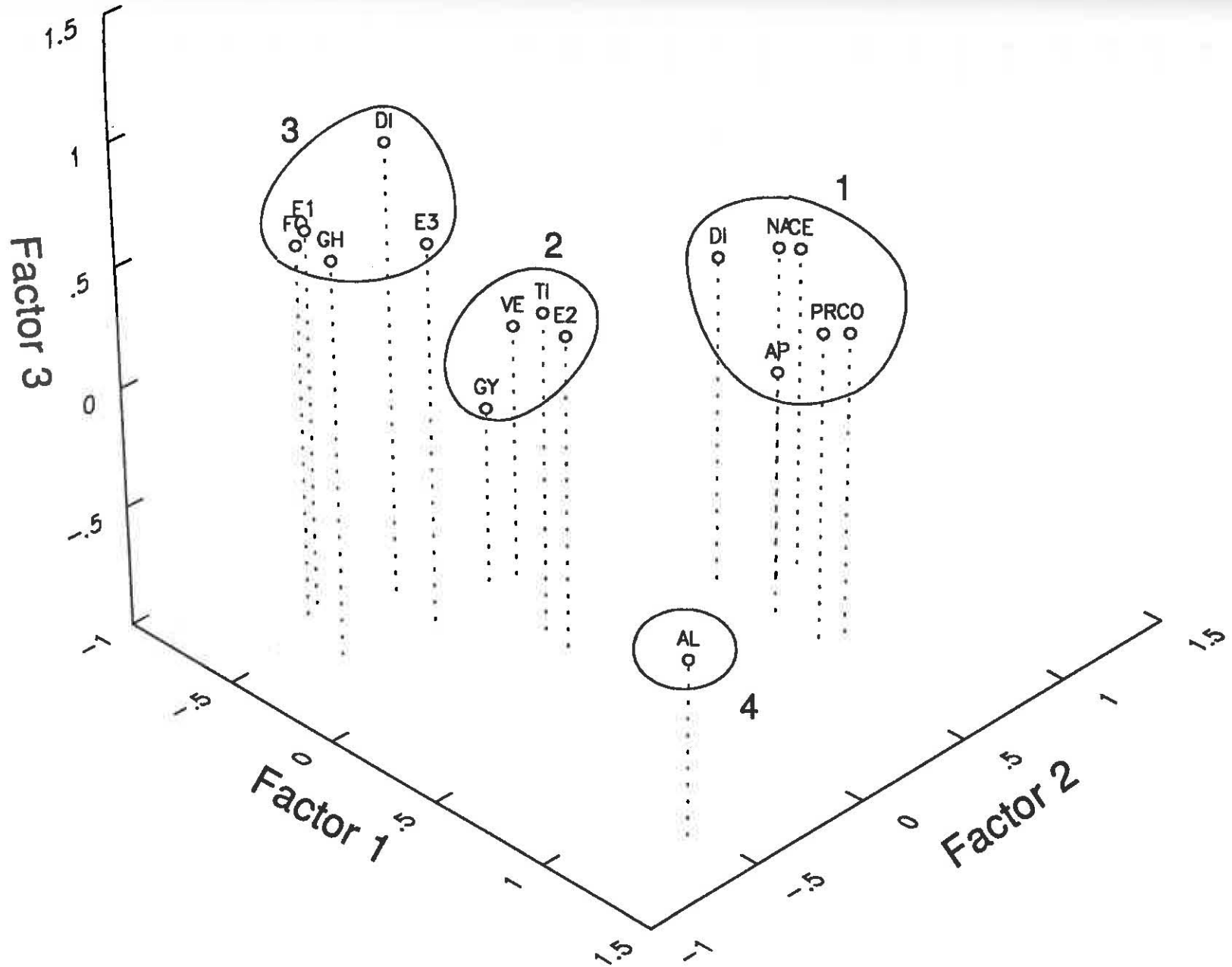

Factor 3
Factor 1
Factor 2
1.5
1
.5
0
-.5
-1
2
1
3
I2
J2
E2
F2
G2
H2
D2
N4
L4
O4
J4
M4
A5
A1
B4
C5
C4
A4
C1
B1
G1

Figure 18. The relationships between the taxonomic groups plotted on the first three factors extracted by Correspondence Analysis. The first three factors explain 81% of the variation in the data set. The clusters have been circled and numbered for easier identification. The codes identifying the groups are: NA-copepod nauplii, CO-copepodites, TI-*Tintinnopsis* spp., AL-aloricate ciliates, PR-*Protoperidinium* spp., CE-*Ceratium* spp., GY-*Gymnodinium* sp., DI-*Distephanus* sp., FO-Foraminifera, GL-*Globigerina* sp., AP-Appendicularia, VE-veliger larvae, E1-50 um eggs, E2-70-80 um eggs, E3-90-100 um eggs, GH-ghost eggs.


Factor 3
1.5
1
.5
0
-.5
-1
Factor 1
-.5
0
.5
1
1.5
Factor 2
-1
-.5
0
.5
1
1.5
3
DI
E1
FC
GH
E3
2
VE
TI
E2
GY
1
DI
NACE
PRCO
AP
AL
4

cluster listed in Table 12.

To determine the strength of the relationships within the clusters shown by the Correspondence Analysis, Spearman Rank Order Correlation Coefficients were calculated among the 16 taxonomic groups, chlorophyll and the physical environmental variables for the transect (Table 13). The results of these calculations were used in conjunction with the Correspondence Analysis results to more clearly understand the relationships between the biotic and physical environments.

The pattern visible in the scatter plot (Figure 17) identifies clusters containing samples collected in (Table 12): (1) the coastal regions and surface stratified water west of the seasonal front, (2) the bottom stratified water west of the seasonal front and the isothermal region east of the front, and (3) the region east of the Liverpool Bay front, i.e., Welsh coast.

The first "sample" cluster contains samples from the upper 40 m at site F (surface stratified water), all three samples from site H (upper 14 m) and the surface sample from site A (Figure 17). The 48-50 m sample at site F was also included in this cluster. The corresponding cluster of taxonomic groups includes copepod nauplii, copepodites, *Ceratium* spp., *Protoperidinium* spp. and Appendicularia (Figure 18). These taxa were found in large numbers at sites A and H (Table 9), and were concentrated in the upper mixed layer at site F. The abundances of the taxa in this cluster were positively correlated with each other

Table 12. A listing of the sample clusters identified by Correspondence Analysis and the corresponding microzooplankton taxa.

Cluster #1

Samples	Microzooplankton
Site A	copepod nauplii
0-3 m	copepodites
Site F	*Protoperidinium* spp.
6-12 m	*Ceratium* spp.
12-16 m	Appendicularia
16-20 m	*Distephanus* sp.
20-25 m	
25-28 m	
28-32 m	
32-36 m	
36-40 m	
48-50 m	
Site H	

Cluster #2

Samples	Microzooplankton
Site C	*Tintinnopsis* spp.
Site D	70-80 um eggs
Site F	90-100 um eggs
40-44 m	ghost eggs
44-48 m	50 um eggs
50-54 m	*Gymnodinium* sp.
54-61 m	Foraminifera
61-66 m	*Globigerina* sp.
61-66 m	veliger larvae

Cluster #3

Sample	Microzooplankton
Site A	aloricate ciliates
3-9 m	
9-12 m	
12-16 m	
16-18 m	
18-22 m	
22-26 m	

Table 13. Spearman rank order correlation coefficients for the Liverpool Bay to Dundalk Bay transect (n=54; $p<0.05=0.268$). Abbreviations are the same as in Table 5.

	nauplii	cope	tint	a cili	Proto	Ceratium	Gymno	Dist	Forams	Globi
nauplii	1.000									
cope	0.744	1.000								
tint	0.271	0.189	1.000							
a cili	-0.078	-0.119	0.591	1.000						
Proto	0.791	0.640	0.141	0.077	1.000					
Ceratium	0.788	0.663	0.120	-0.163	0.779	1.000				
Gymno	-0.080	-0.132	0.236	0.377	-0.160	-0.112	1.000			
Dist	0.319	0.390	0.290	-0.691	0.188	0.231	-0.082	1.000		
Forams	-0.505	-0.596	0.204	0.389	-0.492	-0.454	0.236	-0.254	1.000	
Globi	-0.338	-0.287	0.070	-0.035	-0.306	-0.297	-0.227	-0.093	0.255	1.000

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
nauplii	0.656	0.041	-0.748	0.230	-0.177	-0.381	0.480	-0.122	-0.165	0.627
cope	0.682	-0.003	-0.731	-0.036	-0.316	-0.392	0.373	-0.247	-0.291	0.695
tint	-0.021	0.434	0.014	0.500	0.229	0.412	0.062	-0.428	-0.448	0.161
a cili	-0.080	0.185	0.254	0.510	0.582	0.727	-0.291	-0.374	-0.370	-0.038
Proto	0.643	0.017	-0.609	0.174	-0.068	-0.293	0.410	-0.003	-0.051	0.635
Ceratium	0.727	0.126	-0.643	0.037	-0.264	-0.435	0.500	0.087	0.034	0.534
Gymno	-0.027	0.349	0.123	0.125	0.092	0.291	0.022	0.018	0.008	-0.437
Dist	0.211	-0.146	-0.413	-0.171	-0.091	-0.167	0.047	-0.457	-0.473	0.447
Forams	-0.558	0.327	0.713	0.342	0.409	0.665	-0.324	0.028	0.047	-0.581
Globi	-0.263	0.192	0.346	0.053	0.025	0.152	-0.102	0.103	0.146	-0.146

	append	veliger	egg 1	egg 2	egg 3	ghost	temp	salinity	sigma-t	chl a
append	1.000									
veliger	-0.148	1.000								
egg 1	-0.701	0.207	1.000							
egg 2	0.063	0.215	0.065	1.000						
egg 3	-0.260	-0.099	0.308	0.467	1.000					
ghost	-0.442	0.260	0.479	0.360	0.521	1.000				
temp	0.419	0.137	-0.314	0.092	-0.330	-0.487	1.000			
salinity	0.051	0.037	0.260	-0.034	-0.190	-0.387	0.250	1.000		
sigma-t	0.000	0.008	0.284	-0.045	-0.171	-0.365	0.170	0.984	1.000	
chl a	0.542	-0.231	-0.672	-0.024	-0.234	-0.234	0.045	-0.503	-0.535	1.000

(Table 13).

The coastal water identified by this pair of corresponding clusters is almost identical to the coastal water defined in the previous section (Table 9). The difference is in that Correspondence Analysis excluded *Tintinnopsis* spp. and the deep samples from sites A and F.

The second "sample" cluster includes samples from below 40 m at site F (excepting the sample from 48-50 m) and all samples from sites C and D. In this cluster, there is a progression in the positions of the samples, i.e., samples collected in the bottom stratified water at site F, samples from site D (central channel) and above 11 m at site C (north Anglesey coast), and finally the samples collected below 11 m at site C. Two "taxonomic" clusters (clusters 2 and 3, Figure 18) correspond to this cluster. The "taxonomic" cluster (2) containing *Tintinnopsis* spp., 70-80 um eggs, *Gymnodinium* sp. and veliger larvae corresponds to that portion of the "sample" cluster which contains samples from sites F,D, and the shallow samples from site C. The "taxonomic" cluster (3) containing *Globigerina* sp., Foraminifera, 50 um eggs, 90-100 um eggs and ghost eggs corresponds to that position of the "sample" cluster which contains the deep samples from site C.

Large numbers of *Tintinnopsis* spp., *Gymnodinium* sp., veliger larvae and 70-80 um eggs ("taxonomic" cluster 2) were detected at site D. Seventy-80 um eggs were concentrated below the thermocline at site F (see Figure 14 j). The abundances of *Tintinnopsis* spp. and veliger larvae were

positively correlated with two other taxonomic groups in this cluster (Table 13).

Ghost eggs, Foraminifera, 50 um eggs and *Globigerina* sp. ("taxonomic" cluster 3) were most abundant at site C, and were concentrated below 38 m (see Figures 10 c,f,o,p). The abundances of Foraminifera, 50 um eggs and ghost eggs were correlated with the abundances of two other taxonomic groups in this cluster. The abundance of *Globigerina* sp. was correlated with the abundance of 50 um eggs.

The Liverpool Bay front separated site A from the offshore sites. The samples from this site, with the exception of the surface sample (0-3 m), form the third "sample" cluster (Figure 17). The position of aloricate ciliates in Figure 18 corresponds to the site A cluster. Aloricate ciliates dominated the microzooplankton at this site (mean=$7.1 \times 10^4/m^{-3}$), but decreased rapidly in number west across the transect. Few aloricate ciliates were detected in the 0-3 m sample relative to the other samples from this site (see Figure 8 d). The abundance of aloricate ciliates was negatively correlated with environmental variables (Table 13).

Discussion

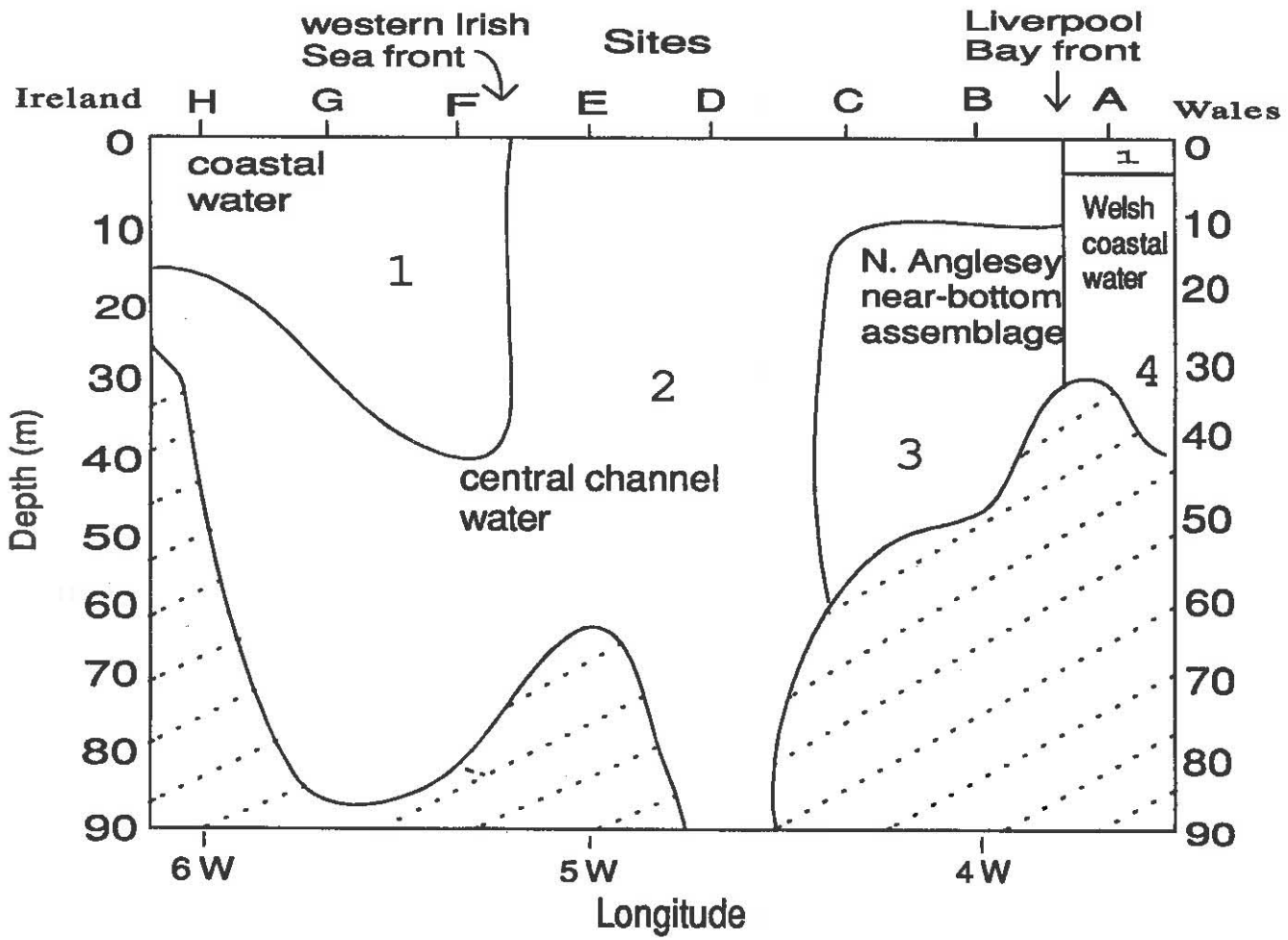
The hypothesis tested in this study states that differences (i.e., in species composition, distribution and abundance) exist between the microzooplankton communities on each side of a front, and that these differences may be associated with interactions (e.g., predation) among the component taxa of that community. The double Longhurst-Hardy Plankton Recorder samples the water column at discrete depths, and permits detailed descriptions of microzooplankton distributions to be produced. It was, therefore, possible to identify or infer some of the relationships between microzooplankton distributions, hydrodynamic features and biotic processes.

Differences in microzooplankton distributions were detected between the western and eastern Irish Sea and may, in part, be associated with the nature of the fronts (i.e., a seasonal front maintained by thermal differences and a non-seasonal front maintained by salinity differences) located in these regions. In the following sections, I will present my interpretation of the results of the Correspondence Analysis, and will describe how the microzooplankton distributions may be influenced by hydrodynamic processes and biological interactions in the region.

Irish Sea water types as defined by microzooplankton distributions

A conceptual model (Figure 19) can be proposed, based

Figure 19. Model developed from the results of the Correspondence Analysis. Each region is characterized by a distinct microzooplankton assemblage: (1) coastal water - copepod nauplii, copepodites, *Protoperidinium* spp., *Ceratium* spp. and Appendicularia; (2) central channel water - *Tintinnopsis* spp., 70-80 um eggs, veliger larvae and *Gymnodinium* sp.; (3) north Anglesey near-bottom assemblage - 50 um eggs, 90-100 um eggs, Foraminifera, *Globigerina* sp. and ghost eggs; (4) Welsh coastal water - aloricate ciliates.


western Irish
Sea front
Sites
Liverpool
Bay front
Ireland
H
G
F
E
D
C
B
A
Wales
coastal
water
1
central channel
water
2
N. Anglesey
near-bottom
assemblage
3
Welsh
coastal
water
4
Depth (m)
0
10
20
30
40
50
60
70
80
90
6 W
5 W
4 W
Longitude

on the results of the Correspondence Analysis. Three water types and a microzooplankton assemblage (a taxonomically distinct region that is not physically different from the surrounding water; see below) seem to exist. These are: (1) the coastal water, (2) the central channel water, (3) the north Anglesey near-bottom assemblage, and (4) the Welsh coastal water. Differences in the microzooplankton assemblages on each side of both the Liverpool Bay and western Irish Sea fronts, as well as on each side of the thermocline in the offshore stratified region were identified from taxonomic distributions. However, Correspondence Analysis identified similarities in the microzooplankton collected in the surface stratified water off the coast of Ireland and the microzooplankton collected in the surface stratified water 48 km to the east (i.e., the region just west of the seasonal front). In addition, Correspondence Analysis identified a distinct microzooplankton assemblage in the deep water off the north coast of Anglesey.

The coastal water includes the upper mixed layers from the coast of Ireland and the region west of the seasonal front. The similarity of the microzooplankton in these regions indicates the possibility that the plankton community west of the front had been advected from the Irish coast (see below). The microzooplankton assemblage off the coast of Wales was similar to the coastal water assemblage, hence the inclusion of the surface sample in this water type. The deep Welsh coastal water differed from the Irish coastal water in the importance of aloricate ciliates.

The inclusion of the bottom stratified water with the central channel water may also be an indication that coastal water is being advected offshore. Only coastal and central channel temperatures were significantly different [Student's $t=5.28$; $p<0.001$ (Table 14)]. However, the microzooplankton in the bottom stratified water was more characteristic of the microzooplankton in the central channel water than the coastal water.

The north Anglesey near-bottom assemblage (NANBA) was not associated with strong physical gradients, with the exception of the Liverpool Bay front along its eastern boundary. The physical variables measured in the region defined by the NANBA differed from those measured on the eastern side of the salinity front, and were consistent with previous findings for Liverpool Bay (Foster et al. 1982a,b). The physical variables measured in the isothermal waters of the NANBA and the central channel were not significantly different when the $p<0.05$ criterion was used for accepting or rejecting the null hypothesis (Table 14). However, the p-values were low in all three cases suggesting there were subtle environmental differences between the regions defined as the NANBA and the central channel. Microzooplankton could be a useful tool for identifying such weak gradients in the physical environment.

Microzooplankton Distributions in the western Irish Sea

The microzooplankton in the stratified region (site F) west of the thermal front was dominated by taxa

Table 14. Results of pooled t-tests. Comparisons of the physical variables measured in the four water types identified by Correspondence Analysis. The water types are: (1) coastal water, (2) central channel water, (3) north Anglesey near-bottom assemblage and (4) Welsh coastal water.

Comparison	Temperature	Salinity	Sigma-t
1 vs. 2	5.28**	-1.41	-1.58
1 vs. 3	12.00**	-0.95	-1.16
1 vs. 4	3.35*	1.15	1.09
2 vs. 3	1.69[a]	1.99[b]	1.89[c]
2 vs. 4	-0.34	8.54**	8.21**
3 vs. 4	1.49	-12.09**	10.24**

(* $p<0.01$; ** $p<0.001$; [a] $p=0.08$; [b] $p=0.06$; [c] $p=0.07$)

characteritic of the coastal sites (e.g., copepod nauplii, *Tintinnopsis* spp., *Protoperidinium* spp. and *Ceratium* spp.). The observed composition is consistent with the advective scenario offered by Khan and Williamson (1970) who reported a weak surface current flowing eastward from the coast of Ireland.

Williamson (1952, see Scrope-Howe and Jones 1985) proposed that the *Calanus finmarchicus* population in the western Irish Sea is not endemic, but is replenished seasonally by a southward flowing current that originates to the north of Ireland where *C. finmarchicus* is abundant. *Calanus* sp. was the dominant naupliar genus at sites F and H, both of which were west of the thermal front. (*Calanus* nauplii were present in only low numbers east of the front.) These observations conform to those from earlier studies of *Calanus* distributions (Scrope-Howe and Jones 1985; Hapette et al. 1991).

The paucity of copepod nauplii, 70-80 um eggs, 90-100 um eggs and ghost eggs at site F suggests that copepod egg production was low at the time of sampling. (The number of copepod nauplii detected at site F was less than half of the number detected at site H.) This low egg production may, in part, be associated with the nutritional environment at this site. A diet deficient in essential nutrients (e.g., sterols, polyunsaturated fatty acids and free amino acids) may result in reduced fecundity in planktonic invertebrates (Stoecker and Capuzzo 1990).

Protozoa have low C:N ratios and are likely to be a

good source of essential nutrients (Stoecker and Capuzzo 1990). Stoecker and Egloff (1987) found that for *Acartia tonsa*, egg production increased ~ 25% when tintinnids were added to a pure algal diet. Stoecker and Capuzzo (1990) speculated that the addition of Protozoa to the diets of other copepod species may have similar effects. The low abundances of both *Tintinnopsis* spp. and aloricate ciliates at site F may have contributed to the low egg production at this site.

Protoperidinium spp. and *Ceratium* spp., on the other hand, were more abundant at site F than at site H off the coast off Ireland. This suggests that at the time of sampling, conditions in the stratified waters at site F, favored the growth of dinoflagellates over copepods. In the Kattegat, Denmark, *Protoperidinium* spp. are most abundant during blooms of several large diatom species (*Thalassiosira* spp., *Thalassionema nitzschioides* and *Chaetoceros* spp.), as well as other dinoflagellates (e.g., *Ceratium* spp.) and silicoflagellates (Hansen 1991). On the other hand, only large species of copepods (e.g., *Centropages* spp.) were able to graze *Ceratium* spp. (Nielsen 1991), and other studies have found that copepods will select against *Ceratium* spp. (Birge 1898; Harvey 1937).

The vertical distributions of *Protoperidinium* spp. and *Ceratium* spp. may have been associated with diurnal vertical migration. Migrating dinoflagellates generally ascend before sunrise and descend near sunset (Olssen and Granéli

1991). Both dinoflagellates were more abundant above than below the thermocline (between 15:40-16:00 h local time when the samples were collected). This distribution is consistent with the results of earlier studies in which dinoflagellates were found to be concentrated in the upper water column as a result of diurnal vertical migration (Blasco 1978; Olsson and Granéli 1991).

It can also be argued that the dinoflagellate distribution at site F resulted from hydrodynamic forcing alone. Blasco (1978) found that swimming speeds slowed when dinoflagellates encountered a density gradient. However, some dinoflagellates have been found to migrate through strong density gradients (Olssen and Granéli 1991).

The vertical distributions of *Protoperidinium* spp. and *Ceratium* spp. at site D in the isothermal region 45 km to the east of site F suggest that species-specific diurnal vertical migration may be associated with different modes of energy acquisition. In laboratory studies, Olssen and Granéli (1991) found the speed and timing of vertical migration, as well as light requirements, varied between dinoflagellate species. In my study, the peak abundance of *Ceratium* spp. [chiefly the mixotroph *C. furca* (Bockstahler and Coats 1993)] occurred between 22-27 m (Figure 12 b). By contrast, *Protoperidinium* spp. are heterotrophic, prey on large dinoflagellates and diatoms (Hansen 1991), were evenly distributed between the surface and 46 m, and had a peak in abundance between 60-64 m (Figure 12 a).

Relatively low abundances of all ciliates at site F

compared with the other sites may, in part, be due to the food environment. The maximum prey size that can be ingested by planktonic ciliates is approximately 43% of the ciliate oral diameter (Heinbokel 1978). Hansen (1991) determined that this limitation on prey size is the reason that ciliates do not respond to the spring bloom of colonial diatoms or to the late summer bloom of large dinoflagellates. The lorica diameter of the most common tintinnid (*Tintinnopsis urnula*) in this study was approximately 50 um. The maximum prey diameter would, therefore, be 21.5 um. This would exclude many of the phytoplankton species detected at this site.

Gymnodinium sp. was present in large numbers along the transect. The average diameter of this dinoflagellate is 15 um, well within the size range that could be consumed by *Tintinnopsis urnula*. It is not clear whether the densities of small organisms are credible, because the gauze used in the LHPR has an aperture of 53 um. However, comparisons between the LHPR and whole water samples collected during a 24-hour anchor station off the Isle of Man, indicated that the LHPR was more efficient at collecting *Gymnodinium* sp. than bottle sampling.

Assuming *Gymnodinium* sp. is a suitable food source (see Kleppel and Lessard 1992), ciliates should not have been food limited. Variability in ciliate abundance, therefore, would rather be linked to predation. Copepods (Stoecker and Sanders 1985; Stoecker and Egloff 1987; Graziano 1989;

Kleppel et al. 1991) and dinoflagellates (Hansen 1991; Bochstahler and Coats 1993) prey on ciliates. Aloricate ciliates and especially *Tintinnopsis* spp. were present in larger numbers at site D than at site F, a distribution opposite that of the copepod nauplii, copepodites and heterotrophic and mixotrophic dinoflagellates.

Vertical distributions of ciliates and dinoflagellates were similar at sites D and F, and may have been associated with the alteration of ciliate swimming patterns in the presence of food (Stoecker et al. 1984). When a tintinnid encounters a dinoflagellate, the ciliate will stop, back up and continue swimming at a slight angle to its original direction. This behavior will maintain the ciliate's position in the algal patch, even if the dinoflagellates are too large to be consumed by the ciliate. Stoecker et al. (1984) further proposed that these patches would be subject to the same hydrodynamic forcing and, as a result, would remain together providing a concentrated food source for larger organisms.

Foraminifera and veliger larvae were abundant below the thermocline at site F, and at site D. The large number of veliger larvae found at site D is consistent with reports that gastropod veligers tend to be abundant in the unstratified waters of the North Sea (Holligan et al. 1984) and Irish Sea (Scrope-Howe and Jones 1985). Foraminifera were found throughout the water column at site D.

Microzooplankton Distributions in Liverpool Bay (eastern Irish Sea)

Variability in the microzooplankton distributions on each side of the front in Liverpool Bay may be due in part to its location in coastal rather than oceanic waters, and to its non-seasonal nature.

The waters of Liverpool Bay are composed of four chemically distinct coastal water types and one offshore water type (Foster et al. 1982a,b). During the spring bloom in early May, these water types are further distinguished by their distinctive phytoplankton communities (Foster et al. 1982b).

Sites A and C should be included in what Foster et al. (1982b) classified as the Lancashire coastal water and Irish Sea water, respectively. In early May, Lancashire coastal water is characterized by a diatom community dominated by *Asterionella japonica*, high chlorophyll concentrations and low silicate concentrations. In May 1989, the surface phytoplankton at site A (i.e., approximately 15 km northeast of Great Orme Head, Wales) was dominated by *Asterionella japonica*. Chlorophyll was at its highest concentration along the transect, while silicate was at its lowest concentration. The diatom community at site C (approximately 45 km west of site A) was more diverse than at site A, but cell abundances were low. The microzooplankton community contained low numbers of coastal taxa (e.g., copepod nauplii, copepodites, *Protoperidinium* spp. and *Ceratium* spp.).

Chlorophyll concentrations were also relatively low compared to the concentrations at site A, while silicate concentrations increased from the concentrations at site A and were in agreement with distributions reported in earlier studies (Foster et al. 1982a,b).

Aloricate ciliates dominated the microzooplankton at site A, but their numbers decreased sharply along the remainder of the transect. It is probable that abundances of aloricate ciliates were underestimated along the transect, especially in stratified waters. During stratified periods in the Northern Adriatic Sea, non-tintinnid ciliates <30 um in diameter often dominated the microzooplankton in numbers and biomass (Revelante and Gilmartin 1983). In this study, a shift in size may have influenced the distributions observed along the transect. The diameters of the aloricate ciliates at site A ranged from 50-60 um, while at site F, diameters ranged from 40-50 um. In addition, LHPR samples were preserved in formalin, which can cause a 30-70% loss in aloricate ciliate abundance (Revelante and Gilmartin 1983).

Protoperidinium spp. and *Ceratium* spp., as well as the majority of the microzooplankton, had a bi-modal distribution at site A. Peaks abundances were generally above 12 m and below 16 m. Copepodites and Appendicularia were the exception to this pattern; the highest abundances of copepodites and Appendicularia were detected in the 12-16 m and 16-18 m samples, respectively.

Khan and Williamson (1970) proposed that currents produced by density gradients were present in Liverpool Bay,

and the presence or absence of these currents determined local chaetognath distributions. The distributions of 70-80 um eggs, 90-100 um eggs and copepod nauplii at site A may also be linked to these currents. Peak abundances of these three groups were detected above 9 m. Eggs are negatively buoyant, passive drifters. They would be expected to settle out of the upper water column or possibly to accumulate at a pycnocline. The density gradient at this station was not strong, however. Copepod nauplii, which typically exhibit little vertical migratory behavior, would not be expected to be found at the surface as a function of their own motions (Huntley and Brooks 1982). The distributions of these groups in the upper part of the water column may have been associated with an offshore-flowing surface current.

While copepod nauplii and copepodites were present in large numbers at site A, 70-80 um egg, 90-100 um egg and ghost egg abundances were also elevated. This suggests that copepod egg production was high during the time of sampling which, in turn, may be linked to the elevated ciliate (1.4×10^4 tintinnids m^{-3} and 7.1×10^4 aloricate ciliates m^{-3}) and dinoflagellate (2.0×10^4 *Protoperidinium* m^{-3}) abundances in this area. Kleppel et al. (1991) reported a strong correlation between egg production and dinoflagellate + ciliate biomass for *Acartia tonsa* in the near-shore waters off Los Angeles. When regressions were performed between the egg production of six copepod species and microplankton

biomass measured at four locations, including the Irish Sea in May 1989, egg production was correlated with dinoflagellate and microzooplankton biomass but not with diatom biomass (Kleppel et al. 1991).

The front in Liverpool Bay appears to be a strong boundary between the coastal and offshore waters. On the western side of the front, at site C, abundances of copepod nauplii and 70-80 um eggs dropped sharply from those detected at site A. At this site, five microzooplankton taxa (e.g., copepod nauplii, copepodites, *Ceratium* spp., Appendicularia, veliger larvae) were at their lowest abundances along the transect, while the abundances of four taxa decreased sharply from site A (e.g., aloricate ciliates, *Protoperidinium* spp., *Tintinnopsis* spp., 70-80 um eggs).

The vertical distribution of the microzooplankton at site C was unique and, as discussed above, may have been influenced by vertical migratory behavior (samples were taken ca. 20:33-20:55 h). Twelve of the sixteen taxa were concentrated below 38 m. *Protoperidinium* spp. and *Ceratium* spp. were concentrated deep in the water column, distributions perhaps associated (at least for *Ceratium* spp.) with a pre-sunset descent (Olsson and Granéli 1991). The distributions of *Tintinnopsis* spp. and aloricate ciliates may have been linked with their response to the movement of the dinoflagellates (Stoecker et al. 1984).

Relatively large numbers of copepod nauplii were detected in the two samples collected between 20-28 m and in the 42-46 m sample at site C. This distribution may have

been associated with the difference in the nauplius species composition at the various depths. Only *Acartia* and *Calanus* nauplii were present in the surface sample (Figure 11). In the 20-24 m sample, *Acartia* and *Calanus* were dominant, while *Eurytemora* dominated the sample collected 6 m from the bottom.

The microzooplankton on each side of the front in Liverpool Bay differ in both composition and distribution. This may be an indication of the front's strength, relative to the abilities of the microzooplankton to penetrate it.

Summary

The variability evident in the microzooplankton distributions along the transect from Liverpool Bay, England to Dundalk Bay, Ireland (May 1-2,1989), appears to be due to hydrodynamic processes associated with the thermal and density structure of the region. Fronts arising from these hydrodynamic processes apparently act as boundaries between the distinct coastal and offshore microzooplankton distributions. However, fine scale variations in the vertical distribution of the microzooplankton at each site appear to be strongly affected by biological interactions (e.g., predation) between taxa.

Correspondence Analysis identified similarities between the microzooplankton assemblages in the surface stratified waters off the Irish coast and 48 km to the east; this indicates that Irish coastal water may be advected offshore. A distinct sub-surface microzooplankton assemblage (11-46 m) not associated with a strong physical gradient was detected off the north coast of Anglesey.

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Appendix

Microplankton abundances along the Liverpool Bay to Dundalk Bay Transect, May 1-2, 1989.

Table 1. Microplankton abundances at site A ($10^3/m^3$).

Depth (m)	copepod nauplii	copepodites	*Tintinnopsis* spp.	aloricate ciliates	*Protoperidinium* spp.
0-3	22.6	3.2	12.9	6.4	24.5
3-9	15.1	0.9	10.4	95.1	23.5
9-12	8.5	2.5	5.9	60.2	20.3
12-16	9.9	7.8	14.2	71.6	15.6
16-18	10.0	4.0	24.0	98.1	26.0
18-22	12.5	2.9	23.1	95.3	24.1
22-26	7.3	5.7	9.0	68.4	6.5

Depth (m)	*Ceratium* spp.	*Gymnodinium* sp.	*Distephanus* sp.	Foraminifera	*Globigerina* sp.
0-3	5.2	21.3	0.6	0	0
3-9	10.4	54.5	0	0.9	0
9-12	1.7	92.4	0.8	0	0
12-16	2.1	44.7	0	0	0
16-18	8.0	46.0	1.0	1.0	0
18-22	7.7	52.9	1.0	0	0
22-26	2.4	92.8	0.8	0	0

Depth (m)	Appendicularia	veliger larvae	50 um eggs	70-80 um copepod eggs	90-100 um copepod eggs	130 um eggs
0-3	0.6	0	0	7.9	9.3	0
3-9	0.9	0.9	0	19.7	2.8	0
9-12	1.7	0	0	3.4	3.4	0
12-16	1.4	0.7	0	7.8	0.7	0
16-18	3.0	1.0	0	4.0	2.0	0
18-22	1.0	0	0	1.0	2.9	0
22-26	3.3	0	0	0	0.8	0

(Table 1. continued)

Depth(m)	200 um eggs	ghost eggs	spiny eggs	*Prorocentrum* sp.	*Cladopyxis* sp.
0-3	0	5.7	6.5	0	0
3-9	0	14.1	5.6	0	0
9-12	0	9.3	1.7	0	0
12-16	0	5.7	2.8	0	0
16-18	0	9.0	3.0	0	0
18-22	0	14.4	0.9	1.0	0
22-26	0	5.7	0	0	0

Depth(m)	*Dinophysis* sp.	*Dictyocha* sp.	Polychaete larvae	Cyphonautes larvae	Rotifers
0-3	0	0	0	0	0
3-9	0	0	0.9	0	0
9-12	0	0	0	0	0
12-16	0	0	0.7	0	0
16-18	0	0	1.0	0	0
18-22	0	0	0	0	0
22-26	0	0	0	0	0.8

Table 2. Microplankton abundances at site C ($10^3/m^3$).

Depth (m)	copepod nauplii	copepodites	*Tintinnopsis* spp.	aloricate ciliates	*Protoperidinium* spp.
0-3	1.5	0	4.2	1.8	1.5
3-7	0.6	0	2.7	1.9	0.6
7-11	0.8	0	2.8	1.3	0.8
11-15	0.3	0	3.2	1.8	0.3
15-20	0.8	0.1	4.2	1.4	0.8
20-24	2.7	0	4.2	3.3	1.2
24-28	2.4	0	5.8	3.4	2.6
28-38	0.9	0	4.1	1.7	0.6
38-42	0.9	0.5	17.1	4.6	2.3
42-46	2.4	0	12.7	6.0	4.8

Depth (m)	*Ceratium* spp.	*Gymnodinium* sp.	*Distephanus* sp.	Foraminifera	*Globigerina* sp.
0-3	0.9	23.9	0.5	0.9	0
3-7	0.8	17.4	0.3	0.6	1.0
7-11	0.3	42.2	0	0.8	3.0
11-15	0.3	18.2	0.2	2.4	2.0
15-20	0	10.0	0	0.7	3.0
20-24	0.6	32.3	0	2.1	3.0
24-28	0.8	26.7	0	1.1	5.0
28-38	0.1	15.5	0.3	0.9	3.0
38-42	1.8	13.8	0.5	6.9	28.0
42-46	1.2	14.3	0	6.0	8.0

(Table 2. continued)

Depth(m)	Appendicularia	veliger larvae	50 um eggs	70-80 um copepod eggs	90-100 um copepod eggs	130 um eggs
0-3	0	0	1.1	2.0	0.5	0
3-7	0	0	0.9	0.4	0.8	0
7-11	0	0.5	1.3	1.5	1.0	0
11-15	0.2	0.2	1.8	0.8	0.8	0
15-20	0	0	1.5	1.0	1.2	0
20-24	0	0	1.5	2.1	1.2	0
24-28	0	0.3	1.8	1.8	1.8	0
28-38	0	0	2.0	0.6	1.0	0
38-42	0	0.9	6.0	3.7	7.3	0
42-46	0	0.8	7.6	2.8	7.5	0

Depth(m)	200 um eggs	ghost eggs	spiny eggs	*Prorocentrum* sp.	*Cladopyxis* sp.
0-3	0	1.8	0.2	0	0.2
3-7	0	5.6	0.1	0	0
7-11	0	9.1	0.3	0	0.3
11-15	0	8.0	0	0	0.3
15-20	0	12.7	0	0	1.4
20-24	0	23.5	0	0	0.3
24-28	0	17.7	0.3	0	0
28-38	0	6.5	0	0	0.1
38-42	0	44.1	0	0.5	0.5
42-46	0	28.6	0.8	0	0

(Table 2. continued)

Depth (m)	*Dinophysis* sp.	*Dictyocha* sp.	Polychaete larvae	Cyphonautes larvae	Rotifers
0-3	0	0	0	0	0
3-7	0	0	0	0	0
7-11	0.3	0	0.3	0	0
11-15	0	0.2	0	0	0
15-20	0.1	0	0	0	0
20-24	0	0	0	0.3	0
24-28	0	0	0	0	0
28-38	0	0	0.3	0.3	0
38-42	0	0	0.9	0	0.5
42-48	0	0	0.4	0.8	0

Table 3. Microplankton abundances at site D ($10^3/m^3$).

Depth (m)	copepod nauplii	copepodites	*Tintinnopsis* spp.	aloricate ciliates	*Protoperidinium* spp.
0-2	1.9	0	6.2	2.3	0.8
2-6	1.7	0	10.9	5.7	1.4
6-12	3.2	4	9.2	4.2	0.7
12-17	0.4	0	15.4	3.3	0.8
17-22	1.2	0	12.9	4.9	1.8
22-27	2.1	0	12.7	3.5	1.4
27-31	2.8	0	17.1	6.4	1.4
31-36	0.4	0	2.7	3.5	1.5
36-40	3.3	0	13.8	5.2	1.3
40-46	1.9	0	8.2	1.9	1.5
46-52	4.3	0	12.8	1.8	0.6
52-57	0.7	0.7	7.1	2.1	0
57-60	1.0	0	6.1	2.1	0.3
60-64	2.9	0.2	2.9	1.0	2.9
64-67	6.6	0	7.1	2.8	1.7
67-72	0.5	0	3.7	1.6	0.2
72-76	0	0.6	0	1.7	0
76-85	2.7	0	5.1	2.7	0
85	1.2	0	4.3	2.4	1.6

(Table 3.continued)

Depth(m)	*Ceratium* spp.	*Gymnodinium* sp.	*Distephanus* sp.	Foraminifera	*Globigerina* sp.
0-2	0.4	63.8	0.4	2.3	1.2
2-6	0	34.1	0	0	0.3
6-12	0	40.0	0	1.8	0
12-17	0.8	54.3	0.4	2.5	0.4
17-22	1.8	115.8	0	1.8	0
22-27	2.8	126.7	0	2.8	0
27-31	1.4	126.8	0	5.7	0
31-36	0.8	71.3	0.4	1.2	0
36-40	1.3	109.8	0	3.3	1.3
40-46	0.5	90.9	1.0	1.0	0.5
46-52	0.6	112.9	0.6	2.4	0
52-57	0	149.2	0	1.4	0.7
57-60	1.3	37.3	0	0.8	0.5
60-64	0.7	34.8	0.2	1.0	0
64-67	1.7	89.8	0	8.8	0
67-72	0.5	41.8	0	0.5	0.5
72-76	1.1	122.0	0	1.7	0
76-85	1.6	62.4	0.4	2.0	0.4
85	1.2	68.3	0	0.4	0

(Table 3. continued)

Depth(m)	Appendicularia	veliger larvae	50 um eggs	70-80 um copepod eggs	90-100 um copepod eggs	130 um eggs
0-2	0.4	0	1.6	5.4	8.9	0
2-6	0.3	0.6	2.3	2.9	2.0	0
6-12	0	0.4	1.8	7.4	3.5	0
11-17	0	0.8	1.3	2.5	2.5	0
17-22	0	1.8	3.1	2.4	0.6	0
22-27	0.7	0.7	2.1	3.5	0.7	0
27-31	0	0.7	2.1	2.8	3.5	0
31-36	0.4	0	5.0	0.4	1.5	0
36-40	0.7	2.0	1.3	3.9	5.2	0
40-46	0	1.5	1.5	1.0	0.5	0
46-52	0	0.6	1.2	1.8	2.4	0
52-57	0	1.4	4.2	1.4	0	0
57-60	0	0.3	2.3	0.8	7.6	0
60-64	0	0.3	1.0	1.0	6.8	0
64-67	0	1.7	1.7	2.7	1.1	0
67-72	0	0.3	0.9	0.7	0.2	0
72-76	0.6	0.6	1.1	0	1.7	0
76-85	0	0.8	2.0	2.3	1.9	0
85	0	0.4	1.6	0.4	7.1	0

(Table 3. continued)

Depth(m)	200 um eggs	ghost eggs	spiny eggs	*Prorocentrum* sp.	*Cladopyxis* sp.
0-2	0.4	5.4	0.4	0.4	0
2-6	0	7.7	0	0.3	0.3
6-12	0	13.7	0	0	0
12-17	0	16.2	0	0	0.8
17-22	0	8.5	0	0	0
22-27	0	14.8	0	0	0.7
27-31	0	7.1	0	0	0
31-36	0	6.5	0	0	0
36-40	0	15.7	0	0	0
40-46	0	8.7	0	0	0
46-52	0	10.3	0	0	0
52-57	0	7.0	0.7	0	0.7
57-60	0	4.8	0.3	0	0
60-64	0	3.9	0.2	0	0.7
64-67	0	13.7	0	0	0
67-72	0	5.5	0	0	0.2
72-76	0	13.4	0	0	0.6
76-85	0	11.3	0.1	0.4	0.8
85	0	8.3	0.4	0	0.8

(Table 3. continued)

Depth (m)	*Dinophysis* sp.	*Dictyocha* sp.	Polychaete larvae	Cyphonautes larvae	Rotifers
0-2	0	0	0	0	0
2-6	0	0	0	0	0
6-12	0	0	0.4	0	0
12-17	0	0	0	0	0
17-22	0	0.6	0	0	0
22-27	0	0	0	0	0.7
27-31	0	0	0	0	0
31-36	0	0	0	0	0
36-40	0	0	0	0	0
40-46	0	0	0	0.5	0
46-52	0	0	0	0.6	0
52-57	0	0	0	0	0
57-60	0	0	0	0	0
60-64	0	0.2	0	0	0
64-67	0	0	0	0	1.0
67-72	0	0	0	0	0
72-76	0	0	0	0	0
76-85	0	0	0	0	0.4
85	0	0	0	0	0

Table 4. Microplankton abundances at site F ($10^3/m^3$).

Depth (m)	copepod nauplii	copepodites	*Tintinnopsis* spp.	aloricate ciliates	*Protoperidinium* spp.
6-12	8.0	1.9	3.5	0.3	12.2
12-16	9.7	0.9	3.1	0	12.2
16-20	10.2	1.2	5.3	0	21.2
20-25	6.4	1.8	4.6	0.4	8.5
25-28	9.8	0.6	5.9	0.3	15.4
28-32	8.0	0.7	1.8	0	7.0
32-36	4.9	1.2	4.3	0.6	3.0
36-40	6.4	1.5	5.8	1.2	6.9
40-44	3.7	0.6	0.6	0	1.9
44-48	4.1	0	1.9	0.6	2.7
48-50	6.7	0.1	2.0	0.3	4.7
50-54	4.4	0.2	4.6	2.5	2.5
54-61	2.6	0	2.6	0.4	2.2
61-66	3.6	0.3	2.6	2.1	2.6
66-72	7.1	0.4	3.6	3.1	5.4

(Table 4. continued)

Depth (m)	*Ceratium* spp.	*Gymnodinium* sp.	*Distephanus* sp.	Foraminifera	*Globigerina* sp.
6-12	7.4	44.3	0.3	0	0
12-16	8.0	19.1	0.7	0	0
16-20	10.6	50.2	0	0	0
29-25	5.9	13.4	0.2	0	0.2
25-28	9.0	20.5	0.3	0.3	0.8
28-32	4.8	37.8	0.2	0	0
32-36	4.9	22.8	0	0.2	0.6
36-40	6.9	36.9	0.3	0.3	1.2
40-44	1.9	33.8	0	0.2	0
44-48	2.3	32.9	0	0.2	0.2
48-50	2.3	11.5	0	0.7	0.1
50-54	2.5	17.7	0	1.1	0
54-61	2.2	69.0	0	0	0
61-66	3.3	30.9	0	1.8	0
66-72	1.8	6.91	0	1.3	0.4

(Table 4. continued)

Depth (m)	Appendicularia	veliger larvae	50 um eggs	70-80 um copepod eggs	90-100 um copepod eggs	130 um eggs
6-12	1.0	0	0.3	0	0	0
12-16	1.7	0.5	0.2	0.3	0	0
16-20	0.4	1.2	0.4	1.2	0	0
20-25	0.9	0.7	0.4	0.5	0.5	0
25-28	1.4	0.3	0.3	0.2	0	0
28-32	0.3	0.8	0.5	0.5	0	0
32-36	1.0	1.0	0.6	0.8	0	0
36-40	1.2	0.6	0.9	1.7	0.9	0
40-44	1.1	0	0.4	1.3	0.2	0
44-48	0.6	0	0.6	1.0	1.0	0
48-50	0.7	0	0.1	3.1	1.0	0
50-54	1.1	0	1.5	3.4	2.5	0
44-61	1.1	0	0.7	3.3	2.5	0
61-66	0.8	0.3	1.5	1.5	3.1	0
66-72	0.4	0.4	1.3	4.7	3.5	0

(Table 4. continued)

Depth (m)	200 um eggs	ghost eggs	spiny eggs	*Prorocentrum* sp.	*Cladopyxis* sp.
6-12	0	0.3	0.3	0	0
12-16	0	0	0	0	0
16-20	0	0	0	0	0
20-25	0	1.1	0	0	0
25-28	0	0.6	0	0	0
28-32	0	0.7	0	0	0
32-36	0	1.4	0	0	0
36-40	0	1.4	0	0.3	0
40-44	0	0.7	0	0.2	0
44-48	0	1.6	0.2	0	0
48-50	0	1.2	0.1	0	0
50-54	0	3.2	0	0.2	0
54-61	0	3.3	0	0	0
61-66	0	8.4	0	0	0.3
66-72	0	6.5	0	0.4	0

(Table 4. continued)

Depth (m)	*Dinophysis* sp.	*Dictyocha* sp.	Polychaete larvae	Cyphonautes larvae	Rotifers
6-12	0	0.3	0	0	0
12-16	2	0.2	0	0	0
16-20	0	0	0	0	0
20-25	0	0	0	0	0
25-28	3	0	0	0	0
28-32	0	0	0.8	0.5	0
32-36	0	0.2	0.4	0	0
36-40	3	0	0	0	0
40-44	0	0.2	0.2	0	0
44-48	0	0.2	0.2	0	0
48-50	0	0.6	0.1	0.3	0
50-54	0	0.2	0	0.4	0
54-61	0	0	0.4	0.4	0
61-66	0	0.1	0	0.8	0
66-72	0	0.2	0.4	0	0

Table 5. Microplankton abundances at site H ($10^3/m^3$).

Depth (m)	copepod nauplii	copepodites	*Tintinnopsis* spp.	aloricate ciliates	*Protoperidinium* spp.
0-4	13.1	7.8	17.3	0	2.8
4-9	14.0	4.1	9.9	0	1.3
9-14	13.4	3.1	8.1	0	1.6

Depth (m)	*Ceratium* spp.	*Gymnodinium* sp.	*Distephanus* sp.	Foraminifera	*Globigerina* sp.
0-4	3.2	20.8	1.6	0.4	0
4-9	3.8	28.0	1.8	0	0.3
9-14	3.1	33.6	1.2	0	0

Depth (m)	Appendicularia	veliger larvae	50 um eggs	70-80 um copepod eggs	90-100 um copepod eggs	130 um eggs
0-4	0.4	0	0.4	1.8	0	0
4-9	1.0	0.3	0	0.6	0.3	0
9-14	0.9	0.6	0	1.9	0.6	0.6

Depth (m)	200 um eggs	ghost eggs	spiny eggs	*Prorocentrum* sp.	*Cladopyxis* sp.
0-4	0	3.2	0	0	0
4-9	0	1.0	0	0	0
9-14	0	0.9	0	0.6	0

(Table 5. continued)

Depth (m)	*Dinophysis* sp.	*Dictyocha* sp.	Polychaete larvae	Cyphonautes larvae	Rotifers
0-4	0	0	0	0.4	0
4-9	0	0.6	0	0	0
9-14	0	0	0.3	0	0